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PERFORMANCE SPECIFICATION AND EVALUATION OF LIAISON ANTENNAS

WRIGHT AIR DEVELOPMENT CENTER
WRIGHT-PATTERSON AIR FORCE BASE, OHIO
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by

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INTRODUCTORY NOTE

This report contains the results of a study of the requirements placed on a long range air-to-ground communications system for military aircraft by the current and proposed operational doctrine of the United States Air Force. This project was originally conducted under contract AF 33(038)-7850, and the first portion of the Final Report* was issued in August, 1951, under that contract. At the time that report was issued it was anticipated that the remainder of the study would be treated in three separate reports. As work on the project continued, however, it became evident that the objectives of the project were better served by combining the final three parts into a single report. This volume is the final result of this effort.

Military Specification MIL-A-9080 (USAF) incorporates the conclusions and recommendations of this investigation, and can therefore be regarded as the culmination of this project. The present report contains a full recounting of the studies on which the requirements embodied in the specification were based, and as such, should be of assistance to the antenna designer who desires a fuller exposition of the argument underlying the specification. It is possible, of course, that some basically new invention will provide an antenna design for liaison communications which was not envisioned in the preparation of the specification. It is equally possible that some change in operational doctrine or procedure will alter the premises inherent to the specification. It is the opinion of the author that the material contained in this report can provide a reasonable basis for altering the specification to meet these contingencies. The essence of the study is described in Chapters 1 through 8 of this report.

The work reported here was carried out over a period of several years. At some time or another, almost the entire staff of the Radio Systems

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* E. J. Moore, H-F Communications Practice of Commercial Airlines, Part I, Final Report on Task III, August 1951 (SRI Project 400), Contract No. AF 33(038)-7850; Stanford Research Institute, Stanford, California.

Laboratory of Stanford Research Institute was involved in this task, and it is therefore not possible to give credit individually for the contributions of every member. Particular credit, however, should be given to Dr. J. V. N. Granger who established the general method of approach to the task and who guided the work during the major part of the investigation; to Dr. W. S. Lucke who suggested the use of average articulation scores as a measure of system performance and the use of signal-to-noise ratio distributions for the experimental evaluation of articulation scores; to Dr. J. Taylor who supervised most of the experimental work and whose suggestions during many discussions contributed significantly to every phase of the work; and to Dr. D. R. Scheuch who acted as Project Leader for the later period of the investigations.

Credit for the success of the flight tests goes to Mr. M. E. Mills who was assisted by Mr. B. D. Pritchard and Mr. R. R. Bagnati, and to Mr. H. F. Dostal who was in charge of the many administrative and maintenance details which the loan of a C-54 aircraft entail. Mrs. L. G. Clarke performed much of the analysis of the tape recordings with utmost efficiency, and also carried out most of the computations which were not done on IBM equipment. The Dayton terminal of the communication link was operated by Mr. V. N. Reese and Mr. R. R. Beams of Wright Air Development Center; their help and cooperation are gratefully acknowledged.

ABSTRACT

In this report the requirements are established for a practical performance specification for airborne liaison antenna systems. The liaison system utilizes frequencies between 2 Mc and 30 Mc for which propagation is preponderantly by sky waves; communications take place between aircraft and ground stations. The wavelengths are comparable in magnitude to the dimensions of the aircraft, so that currents on the airframe itself provide a large part of the useful radiation. Flush-mounted antennas which are desirable for high-speed aircraft are an integral part of the airframe and any change in antenna design may entail considerable structural changes of the airframe. The specification must therefore be based almost entirely on tests which can be performed before the actual aircraft is built, that is, on data obtained from models and mocked-up sections of the airframe.

The measure of antenna performance for the purposes of the specification is the antenna system efficiency. The efficiency requirements of a proposed antenna are expressed relative to the antenna system efficiency of a reference antenna, the performance of which is known from past experience. It is shown that this system of rating antennas is intimately related to the articulation score method of rating voice communication systems. The effect of the antennas is measured by the change in these scores produced when using the proposed antenna instead of the reference antenna as a part of the air-to-ground communication system.

Liaison communications take place under a large number of different ionospheric conditions, for many different orientations and locations of aircraft and ground stations, and for any frequency in the range under discussion. Since it is very difficult to compare antennas directly, taking account of all of these variables, it is desirable to express the worth of an antenna by means of a single factor of merit. A weighted average of the articulation score for all these links is therefore taken as such a factor of merit. The weight function is given by the relative number of times a particular link is expected to take place. This function

is determined from a study of the way in which the system is used by the military services. It is shown that a simple approximation to the weighting function is satisfactory for use in a practical specification.

The relationship between antenna ratings based on average articulation scores and those measured by the antenna system efficiency was established by an analysis of a large number of radiation patterns of several high-frequency antennas on several different aircraft. These patterns were measured on models of the aircraft involved.

Extensive flight tests using a C-54 aircraft with several high frequency antenna systems demonstrated the equivalence of data obtained from model measurements with those measured during actual operations of a full-scale aircraft. The requirements in the specification based on measurements on aircraft models are therefore fully justified.

Appendix A of this report is a copy of the complete specification. Other appendices describe in detail some of the theoretical and experimental investigations, only the results of which are cited in the report proper.

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APPENDIX I

PERFORMANCE SPECIFICATION AND EVALUATION OF LIAISON ANTENNAS

CHAPTER 1

INTRODUCTION

Most present-day aircraft employ externally mounted antennas for use with their communications and navigation transmitters and receivers. These antennas have hitherto been regarded as a piece of equipment only loosely related to the many different types of aircraft on which they were to function. At the higher aircraft speeds now coming into use, antennas which blend completely into the aerodynamic structure of the aircraft are required. Inasmuch as such flush-mounted antennas form an integral part of the airframe, the responsibility for their design must be jointly shared by the antenna engineer and the airframe designer.

The antennas to be discussed in this report are part of the air-to-ground and ground-to-air liaison system which utilizes frequencies in the range from 2 to 24 Mc. Airframe dimensions and wavelengths are of comparable magnitude; the aircraft as a whole acts as the radiator and the "antenna" serves to excite the required currents over the aircraft skin. In order to accomplish this excitation, a substantial part of the airframe must be isolated electrically from the remainder of the aircraft. Consequently, the liaison antenna imposes the requirement for major structural changes on the airframe. It therefore becomes essential that the antenna design be practically completed simultaneously with the design of the rest of the aircraft. Only minor changes can be made on the antennas after the prototype of a new aircraft has been built and is ready for flight testing.

In addition to the necessity of deciding on the design of the antenna proper at an early stage of the development of the aircraft, the antenna characteristics must be known far enough in advance in order that a suitable antenna matching unit can be developed. Without such a coupler the

antenna is useless. Since these matching units must be located close to the antenna gap, they must be either automatic in their operation, or they must at least be remotely tunable from within the aircraft cabin. Coupler design is a lengthy and costly process. Knowledge of the impedance characteristics of the proposed antenna will insure that a coupler can be developed in time to be available when the aircraft is ready for flight testing of the liaison system. In general, it will be preferable to design the antenna in such a fashion that it can be used in conjunction with existing matching units. For the reasons already stated, the fact that this can be done must be established at an early stage of the antenna development.

The work reported here was undertaken for the purpose of determining performance parameters descriptive of the liaison system which can be predicted in advance from model and mockup measurements. The criteria on which the performance measures are based not only take account of the electrical properties of the antennas but also view these properties in the light of the operational demands on the h-f communication system. The results of these investigations are incorporated in a specification for the design of aircraft liaison antennas. An antenna system which satisfies the standards of performance required by this specification will be at least as good as, or better than, presently used h-f aircraft antennas. A summary of the specification is given in Chapter 2 of this report. A copy of the complete specification will be found in Appendix A.

In Chapter 3 the operational use of the h-f liaison system is discussed. The emphasis is placed on those factors which will ultimately enter, in a quantitative fashion, into the antenna performance evaluation. In Chapter 4 the physical properties of the air-to-ground link are described. High frequency transmissions take place via the ionosphere, the properties of which play a dominant role in the performance of the system as a whole. Another fundamental physical limitation of the antennas themselves is the comparable size of airframe and wavelengths. This restricts the differences between radiation patterns, impedance functions, and other electrical properties of possible antenna structures which might be used on the same aircraft.

Several performance criteria are formulated in Chapter 5. Articulation scores as observed over the liaison system are proposed as the primary measure of system performance, on the basis of which different antennas are to be compared. As will be demonstrated, however, it is not

necessary to ever conduct articulation tests during the antenna development. The actual measure of antenna system performance is the increase or decrease in signal power which is required to make the average articulation scores observed over a proposed antenna system equal to those observed over a reference antenna system. This measure of an antenna's worth can be simply expressed as a ratio of antenna system efficiencies which, in turn, can be accurately predicted from measurements on models of the aircraft.

The standards of performance required for an adequate antenna system are established in Chapter 6. The choice of the fixed-wire antenna for the reference antenna system is explained. It is shown that the wide band of frequencies utilized by the liaison system leads to separate performance requirements for the low end of the band, and for the upper end of the frequency range of interest.

An extensive program of flight testing was undertaken to show that the performance ratings based on antenna system efficiencies correspond to those obtained from articulation tests carried out over the actual air-to-ground or ground-to-air links. These flight tests are described in Chapter 7. The results of these experiments fully justify the recommended methods of testing and the requirements of the specification.

All proofs and detailed descriptions of tests are described in separate appendices. The essential arguments which led to the specification are thus contained in the report proper without being obscured by a large amount of detailed discussion. Each of the appendices was written, as far as possible, in the form of a self-contained paper in order to avoid a large amount of cross-referencing. Such a procedure necessarily leads to some duplication. It is hoped, however, that the resulting increase in volume will be counterbalanced by the greater usefulness of the report as a whole.

Finally, in an investigation of this kind, many approaches may be tried which are ultimately discarded or modified. Some of these approaches are of interest in themselves, however, and are therefore described in separate appendices.

CHAPTER 2

SUMMARY OF SPECIFICATION[1]

A specification[*] for the design of antennas for liaison communication equipment has been prepared, the requirements of which are based on the investigations reported here. The chief aim of this specification is to insure that communication systems which employ antennas satisfying its requirements will provide adequate communications for the United States Air Force. In addition, however, it provides an outline for the procedure to be followed in the design of cap-type antennas. Such antennas consist of isolated portions of the vertical stabilizer or of isolated wing tips. These configurations have been found to satisfy most consistently the requirements of the specification. The design of such antennas will be described in detail in a forthcoming report.

The specification is based primarily on a consideration of the operational demands on the h-f communications system. In other words, the requirements on radiation patterns, impedance, efficiency, etc. are determined on the basis of the role which these parameters play in the operational utilization of the communications system, rather than on some arbitrary numerical standard. The acceptable ranges of electrical characteristics detailed in the specification are all stated on a relative basis. That is, the proposed antenna system is required to perform to a certain standard of excellence relative to the performance which would be obtained if a standard fixed-wire antenna system were employed on the same aircraft, for the same communication purpose.

There are several reasons for specifying the requirements in relative terms. The most important of these is the choice of articulation scores

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[*] Military Specification MIL-A-9080 (USAF). A copy of the specification is included as Appendix A of this report.

[1] The content of this chapter is taken essentially from the following paper presented at the Second Symposium on the USAF Antenna Research and Development Program, Monticello, Illinois, October 1952: J. V. N. Granger, E. J. Moore, and W. S. Lucke, "Performance Requirements for Airborne Liaison Communications Antennas."

as a measure of system performance. This measure is basically a means of comparison of various systems intended to fulfill the same functions. For the purpose of establishing performance standards, therefore, a reference system is required. Because the specification is intended to cover the antenna developments for a wide variety of military aircraft which differ greatly in size and in configuration, a different reference system is needed for each of these aircraft. Finally, the reason for making the performance specifications relative to the performance of a standard fixed-wire antenna, is that this antenna has had wide utilization for many years and has generally proven satisfactory, at least from the standpoint of its electrical characteristics.

An important feature of the specification is that it is designed in such a way as to permit an evaluation of the proposed antenna on the basis of measurements and calculations performed in the laboratory. It is not necessary to build and fly a full-scale model of the proposed antenna system in order to determine whether or not it will meet the specifications. The series of flight tests which will be described in this report were undertaken for the purpose of demonstrating that the required laboratory measurements provide essentially the same data on the antennas which would be obtained from meaningful tests on the completed aircraft.

Before proceeding with an outline of the specification, it is necessary to define some terms.

Radiation pattern efficiency, η_p, is defined as the ratio of the power radiated into the solid angle useful to communications, to the total radiated power. Study of long-distance h-f propagation shows that for the distances involved here, and for frequencies above about 6 Mc, the solid angle useful to communications is the angular range extending from 30 degrees above the horizontal plane through the aircraft to 30 degrees below that plane. In strategic and tactical operations, the useful solid angle extends over all angles in azimuth. In transport operations, the useful angular range in azimuth may be confined primarily to the quadrants forward and aft of the aircraft.

Antenna power transfer efficiency, η_a, is defined as the ratio of the total radiated power, to the power input at the antenna terminals.

Antenna matching circuit efficiency, η_c, is defined as the ratio of the power input to the antenna terminals, to the power input to the matching circuit.

Power transfer efficiency of the transmission line, η_t, is defined as the ratio of the power input to the antenna matching unit, to the power input to the transmission line at the transmitter output terminals.

Antenna system efficiency, η_s, is the ratio of the power radiated into the desired solid angle, to the total power input at the transmission line terminals. It is therefore given by the following product:

$$\eta_s = \eta_p \eta_a \eta_c \eta_t \ . \tag{1}$$

Power transfer efficiency of the antenna system, η_{tr}, is defined as the ratio of the power radiated into space, to the power input at the transmission line. It is therefore given by the following product:

$$\eta_{tr} = \eta_a \eta_c \eta_t \ ; \tag{2}$$

and the antenna system efficiency is given by:

$$\eta_s = \eta_{tr} \eta_p \ . \tag{3}$$

The proposed specification places independent requirements on the antenna performance in the frequency range from 2 to 6 Mc and from 6 to 24 Mc. Experience has shown that for the latter range, and for the sizes and configurations of the aircraft which are involved, almost any antenna system of reasonable design will provide an adequate power transfer efficiency. Also, in the 6 to 24 Mc Range, the input impedance of any reasonable form of h-f antenna can be matched to the 50 ohm transmission line with reasonably good efficiency. In this frequency range then, the best antenna for the job is that which has the best radiation pattern efficiency, provided of course that the resistive losses are not excessive.

In the frequency range from 2 to 6 Mc there is very little difference between the radiation pattern efficiencies of the various possible antenna configurations for the size of airframes involved. It is therefore not necessary to specify the pattern characteristics of the desired antenna in this range. On the other hand, it is in this frequency range that the greatest difficulties are encountered in efficiently matching the input impedance of the various possible antenna configurations to a 50-ohm transmission line. The proposed specification is therefore based on the

requirement for good power transfer and matching circuit efficiencies in the 2 to 6 Mc range.

The specification requires that the antenna system efficiency of the proposed antenna and of the reference fixed-wire antenna shall be determined at frequencies of 6, 8, 10, 12, 14, 16, 18, 20, 22, and 24 Mc. The antenna system efficiency is actually determined by its individual components. The radiation pattern efficiency is obtained from radiation patterns measured on models of the aircraft. The antenna matching circuit efficiency is obtained from bench tests on the prototype coupler, or, in the event that development of the coupler has not been completed, from standard charts which are included as a part of the specification. The power transfer efficiency of the transmission line can be computed from the known line length, attenuation, and limiting VSWR.

A method of estimating the antenna power transfer efficiency for cap-type antennas is described in the specification (Appendix A). For these antennas, the antenna power transfer efficiency depends primarily on the loss characteristics of the dielectric structure employed in the gap section. In shunt-fed antenna systems, on the other hand, the antenna power transfer efficiency depends primarily on conductor loss in the feed conductor. Methods for estimating the antenna power transfer efficiency in these c ses are left to the discretion of the design engineer.

The proposed specification places a dual requirement on the antenna system efficiency at each of the frequencies named. The antenna system efficiency of the proposed antenna must be at least 50% of the antenna system efficiency for the reference antenna at each of the specified frequencies. Furthermore, the average antenna system efficiency for the proposed antenna must be no less than that for the reference fixed-wire antenna. In making these computations, the specification provides that the antenna system efficiency of the reference fixed-wire shall be taken as 0.9 times the radiation pattern efficiency of the reference antenna, as obtained from model pattern measurements. Stated in other terms, this part of the specification requires that the antenna performance in the frequency range from 6 to 24 Mc must, on the average, be as good as that which would be obtained from a standard fixed wire on the same aircraft, and at any given frequency the performance of the proposed antenna must be at least half as good as the performance that would be obtained with the fixed-wire antenna.

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For the 2 to 6 Mc range, the specification requires that the antenna system efficiency shall be not less than 25% at any frequency within this range, when the radiation pattern efficiency is taken as unity. Further, the *average* antenna system efficiency in this range is required to be at least 50%. In order to protect the designer who must deal with a small airframe, the specification provides that these requirements must be met only for that part of this frequency range in which the overall dimensions of the aircraft exceed stated values. If this were not done, the specification could be met only through the use of matching elements with entirely impractical quality factors.

The requirements outlined above are, of course, only part of those contained in the specification. Choice of materials, lightning and corona protection, limiting VSWR's on the feed cable, and many other factors are treated in the specification itself. Almost all the data required for proof of performance of a proposed antenna system can be obtained through calculations and model measurements. It is therefore possible for the antenna designer, and contracting agency of the Air Force, to determine at an early stage in its development whether or not the proposed antenna system will meet the requirements when the design is reduced to practice. This is an essential feature of a specification for an airborne antenna which involves the primary structure of the airframe. If the acceptability of the antenna cannot be determined until it is built and flown, the commitment in time and money which has already been made when the antenna is tested is too great to make rejection of even a poor design practical. The choice of performance measures and requirements on which this specification is based will be discussed and justified in the remainder of this report.

CHAPTER 3

THE H-F COMMUNICATION SYSTEM IN THE AIR FORCE

Before it is possible to judge the performance of high frequency aircraft antennas, one must first know the tasks assigned to the liaison system as a whole, and the way in which the system is used in order to fulfill these functions. The importance of the different electrical parameters of the antennas can then be evaluated by their influence on the overall performance of the communication system. A detailed study of liaison communications was therefore undertaken. For this purpose, questionnaires were prepared and sent to the various units of the Air Force. Information obtained in this fashion was supplemented by interviews with operating personnel of some of the Bomb Wings of the Strategic Air Command, and with the Planning Section of the Strategic Air Command Headquarters. A similar survey of commercial airline operations was also undertaken. Although military and commercial procedure may differ considerably, it was felt that much could be learned from the airlines' extensive experience with h-f communications, in flights over a limited number of fixed routes. The results of the survey of h-f communications practice of commercial airlines are discussed elsewhere.[1]

In both civilian and military communications, high frequencies are used primarily for liaison purposes between an aircraft and a ground station. Such properties of the system as the distribution of ground stations with respect to the aircraft, the relative importance of the different frequencies within the range of interest, and the kind of modulation used are all related to the way in which the suitability of the electrical properties of the antennas are to be judged. The performance evaluation of the antennas also depends on the length and relative importance of messages sent out, or received by the aircraft; the type and extent of vocabulary used, in the case of voice modulation; the altitude at which

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[1] E. J. Moore, H-F Communications Practice of Commercial Airlines, Part I, Final Report on Task III, August 1951 (SRI Project 400), Contract No. AF 33(038)-7850; Stanford Research Institute, Stanford, California.

the aircraft normally operates; the frequency of occurrence and severity of precipitation static; and many other such properties which are characteristic of the system as a whole. The surveys of h-f communication practices were undertaken with these factors in mind.

In the Air Force, the Strategic Air Command, the various transport services, and the Air-Sea Rescue Service are the principal groups which utilize h-f communications. The requirements on the system are most severe in the Strategic Air Command, where an aircraft may be several thousand miles away from the nearest friendly ground station. Requirements of the transport services, on the other hand, are often similar to those of some of the commercial airlines.[1]

The investigation of the liaison system has given the following results of importance to the evaluation of high frequency aircraft antennas for military use:

The radiation patterns of the antennas should cover equally all azimuthal directions with respect to the aircraft. Since transport aircraft in military service do not always fly over established routes, this requirement applies to this type of operation as well.

The liaison system is required to operate over distances of up to 3000 miles between transmitter and receiver. The minimum distance over which the high-frequency system is used is of the order of 100 miles or less. It will be found that differences in performance between possible aircraft antenna systems are small, and these differences are therefore most important when the reliability of the communication links tend to be marginal. Transmissions over long distances should therefore be given major emphasis in antenna evaluation.

Another significant factor is the relative importance of the different frequency channels in the high-frequency range. As far as the present methods of skywave frequency predictions allow, the highest available frequency below the maximum useable frequency is almost always used for transmission. It is theoretically possible to determine in advance the optimum frequencies for transmissions over all the paths which will be used by the different services of the Air Force during the next few years, and so obtain the probability of using any of the available frequencies. The

[1] E. J. Moore, *Op. Cit.*

evaluation of these frequency-use probabilities can be carried out in practice, for transport operations which take place over definite, known routes. Such a study has been made using a limited number of paths and a limited number of ionospheric conditions. This is described in Appendix C. Although the frequency-use probabilities calculated in Appendix C varied over a wide range the inclusion of such weighted averaging with frequency, in evaluating antenna performance, did not seem to influence significantly the ratings obtained for the various antenna systems. The determination of the frequency-use probabilities applicable to bombers and reconnaissance aircraft is not possible without much more detailed knowledge than is presently available, of the routes to be flown during missions, the distribution with the time of day of such missions, and the months and years when these operations will take place. It is reasonable to assume, however, that the much greater number of possible ionospheric conditions and transmission paths to be expected for these operations will cause a more uniform use of all available frequencies than was found for the transport services. The assumption will therefore be made here that, on the average, no one of the available frequencies will be used more often than any of the others.

The performance of antennas differs fundamentally in receiving and transmission. The relative importance to the system of these two cases must therefore be determined. The most important types of messages in bombing operations originate on the ground and are received on the aircraft. This would indicate that major emphasis in the evaluation problem should be placed on the reception of signals on the aircraft. On the other hand, space and weight limitations restrict the available transmitter power for the airborne installation, and the size and shape of the aircraft itself, narrowly circumscribe the possible antenna configurations. It is clearly important then to use these limited airborne transmitting facilities in the most efficient way. As will be shown later, all reasonable airborne antenna systems perform about equally well in receiving. The choice between different h-f aircraft antenna systems must therefore be based on a comparison of transmissions from the aircraft.

Most air-to-ground and ground-to-air liaison communications are carried out today by the use of radio telephone instead of radio telegraph.[1]

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[1] See C. L. Christian, "PAA's Radio Phone Girdles Globe," *Aviation Week*; December 11, 1950.

A large part of the vocabulary transmitted consists of the words of the phonetic alphabet. Such a system lends itself to an evaluation based on the fraction of the transmitted words correctly identified at the receiver, that is on the articulation score, and this is the scheme which will be adopted here as a fundamental measure of performance.

The high-frequency aircraft antenna used most frequently at the present time, consists of a wire strung between the vertical stabilizer and the forward end of the fuselage. The surveys of both military and commercial liaison communication practices indicate that satisfactory operation of the h-f system can usually be achieved when using this antenna system. The performance of the fixed-wire antenna has therefore been chosen as a reference, relative to which other proposed antennas will be compared.

Reliable communications during long-range missions of the Strategic Air Force is the most severe requirement demanded of the liaison system. The purpose of the specification will be to insure that the airborne antenna provides the best possible help in this task. At the same time it will give adequate service for the many other functions required of the system

CHAPTER 4

PHYSICAL PROPERTIES OF THE LIAISON SYSTEM

A. INTRODUCTION

The previous chapter described the tasks which the liaison system must perform and the operational procedures used to achieve them. In this chapter the physical limitations of the system will be discussed, especially insofar as they affect the performance of the h-f aircraft antenna and the way in which antenna performance can best be judged.

High-frequency communications utilize sky-wave transmission. The state of the ionosphere therefore determines to a large extent the quality of the air-to-ground or ground-to-air link at any given time or place. Even under normal ionospheric conditions the signal-to-noise ratio may vary over a range of 20-30 db within periods of minutes. The differences in gain between possible h-f aircraft antennas are small in comparison since the patterns of all such antennas depend on the limited number of modes of current flow which can be excited efficiently on the aircraft structure. The impedance of the antennas as a function of frequency is also closely related to the dimensions of the airframe, which thus determines the maximum achievable efficiency of power transfer between transmitter and space. Finally, the available power of a transmitter on an aircraft is limited by the size and weight of the equipment.

The liaison system is used for the transmission of intelligence in the form of spoken words. The fraction of words correctly understood is therefore a measure of the effectiveness of the communication link. This fraction, which is called the articulation score, will form the basis for the comparison of different proposed h-f aircraft antenna systems.

B. SKY-WAVE TRANSMISSIONS AND ATMOSPHERIC NOISE

Because of its dominant role in the system, a brief description of the ionosphere may be helpful.[1] The term "ionosphere" refers to an

[1] For a more complete treatment of this subject see: National Bureau of Standards, Ionospheric Radio Propagation; Circular 462, June 25, 1948.

ionized region of the upper atmosphere starting at a height of about 50 km above the earth's surface. For practical purposes ionization may be thought of as occurring in distinct layers. During the day there are three of these: the *E*-layer at a height of about 110 km, the *F1*-layer at about 200 km, and the *F2*-layer between 300 and 500 km above the surface of the earth. At night the *E*-layer ion-density becomes too small to permit communications between points on the earth's surface at the frequencies of interest here. At the same time, the *F1*- and *F2*-layers coalesce to form a single nighttime layer which is also called the *F2*-layer. These ionized layers are formed in a complicated and only partially understood manner by radiations from the sun. The degree of ionization varies with the zenith angle of the sun and with the degree of sunspot activity. The height of the *E*-layer remains practically constant, but the *F2*-layer height varies with the time of day, the season, and the period of the sunspot cycle.

Interaction between an electromagnetic wave and the free electrons of the layers causes the wave to be refracted. If the frequency of a wave vertically incident on one of these layers is below a certain critical value, it is returned to the earth; above this critical frequency it passes through the layer. The critical frequency is proportional to the square root of the electron density and is therefore greatest for the *F2*-layer, and least for the *E*-layer. The critical frequencies of waves which impinge on the ionosphere at oblique angles are roughly proportional to the product of the vertical incidence critical frequency and the secant of the angle of incidence. The height of the layer, together with the angle of incidence of the wave on the layer determine the distance between the transmitter and a possible receiver location. The critical frequency at oblique incidence is therefore called the maximum usable frequency (muf) for transmission over a given distance via a given layer. Since the critical frequency varies with the activity of the sun, the muf for a given path also varies between widely spaced limits. It is for this reason that the liaison system is required to operate over such a large range of frequencies — from 2 Mc to about 30 Mc.

To illustrate the various possible transmission paths taken by the sky wave, consider transmissions from a point *A* to a point *B*, both on the earth's surface, as shown in Fig. 1. For frequencies below the maximum usable frequency (muf) for the *E*-layer the wave is refracted by this layer and follows the path, *ACB*. If the frequency is now increased above the muf for the *E*-layer, a point will be reached where a wave at a steeper

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angle of incidence will penetrate this layer at the point C', and travel to the $F2$-layer.* The wave is refracted there, and returned to the receiver. Two signal paths are now possible; the original path ABC, using the E-layer, and the path ADB, via the $F2$-layer. If the frequency is increased still further beyond the E-layer muf for the path AB, the wave will penetrate the E-layer at the point C, and the E-layer mode of transmission will become inactive. Frequencies up to the $F2$-layer muf can be

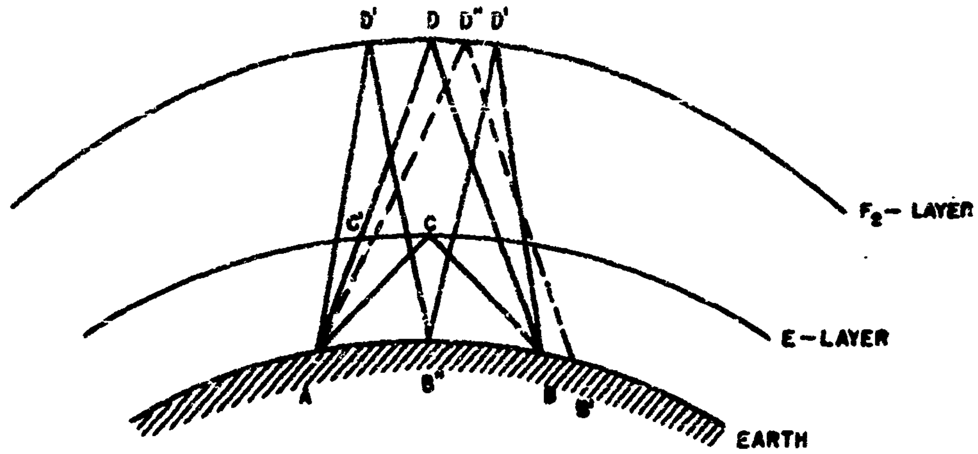

FIG. 1

SKY-WAVE TRANSMISSION PATHS

A-6060-F-242

used for transmissions over the path ADB, beyond which the wave is no longer refracted back to earth at the point D. Higher frequencies will, however, reach points beyond B, such as B', up to distances where the ray leaves the transmitter tangent to the earth. Under the conditions assumed here, the $F2$-layer muf is also the maximum usable frequency for transmissions from A to B. Conversely, transmissions at the muf will not reach any point between A and B.** The area about A not reached by the sky wave is called the skip zone.

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* The $F1$-layer is here omitted for illustrative purposes.

** The small coverage area of the ground wave is neglected here.

Other sky-wave paths are possible at intermediate frequencies. One of these is shown in Fig. 1. The wave here is returned to earth by the $F2$-layer at a point B'', half way between A and B, where it is reflected back to the ionosphere to reach the receiver at B after two hops. Operation near the muf, however, will eliminate this two-hop path. Transmissions to points beyond those reached by the tangent ray are made possible by such multi-hop paths.

Electromagnetic waves are not only refracted by the ionosphere but also attenuated. The free electrons set in motion by the waves are subject to collisions in which some of the energy of the wave is dissipated. The number of collisions depends on the mean free path of particles in the upper atmosphere, and on the range of motion of the electrons. The latter is proportional to the square of the wavelengths. If P_0 is the unabsorbed power density at the receiving point, the actual power density can be written in terms of an absorption index α as

$$P = P_0 10^{-2\alpha} . \qquad (4)$$

For the range of frequencies of interest here, α is inversely proportional to the square of the frequency. The mean free path decreases with increasing pressure. Maximum attenuation at a fixed frequency will therefore be experienced in the lowest region of the ionosphere, despite the small degree of ionization found at these altitudes. This absorbing region situated below the E-layer is usually called the D-layer. The absorption index depends also on the degree of ionization of this D-region, and it therefore varies with the temporal changes of the sun's activity. In particular, D-region ionization during the night becomes so small that the waves are negligibly attenuated. Maximum attenuation occurs at noon and it increases as the point of ionosphere penetration of the wave approaches the earth's equator.

Atmospheric noise is another important phenomenon of high-frequency communications. This noise is caused by thunderstorms and can travel to any part of the earth's surface by way of the sky wave, in the same way as the signal. The shape of the individual noise pulses produces a power spectrum approximately inversely proportional to the square of the frequency. Atmospheric noise intensity at a given place is subject to the same changes with ionospheric conditions as a signal would be which travelled over the same path. Let us examine the signal-to-noise ratio at

a receiving site far enough removed from thunderstorm areas so that atmospheric noise reaches it by the sky wave only. The frequency of transmission from a transmitter at T to a receiver at R at a distance of d, is assumed to be the maximum usable frequency for the path. Noise sources within an approximately circular area of radius d about the receiver are located within the skip zone and therefore do not contribute to the receiver noise. This situation is illustrated in Fig. 2. Similarly a

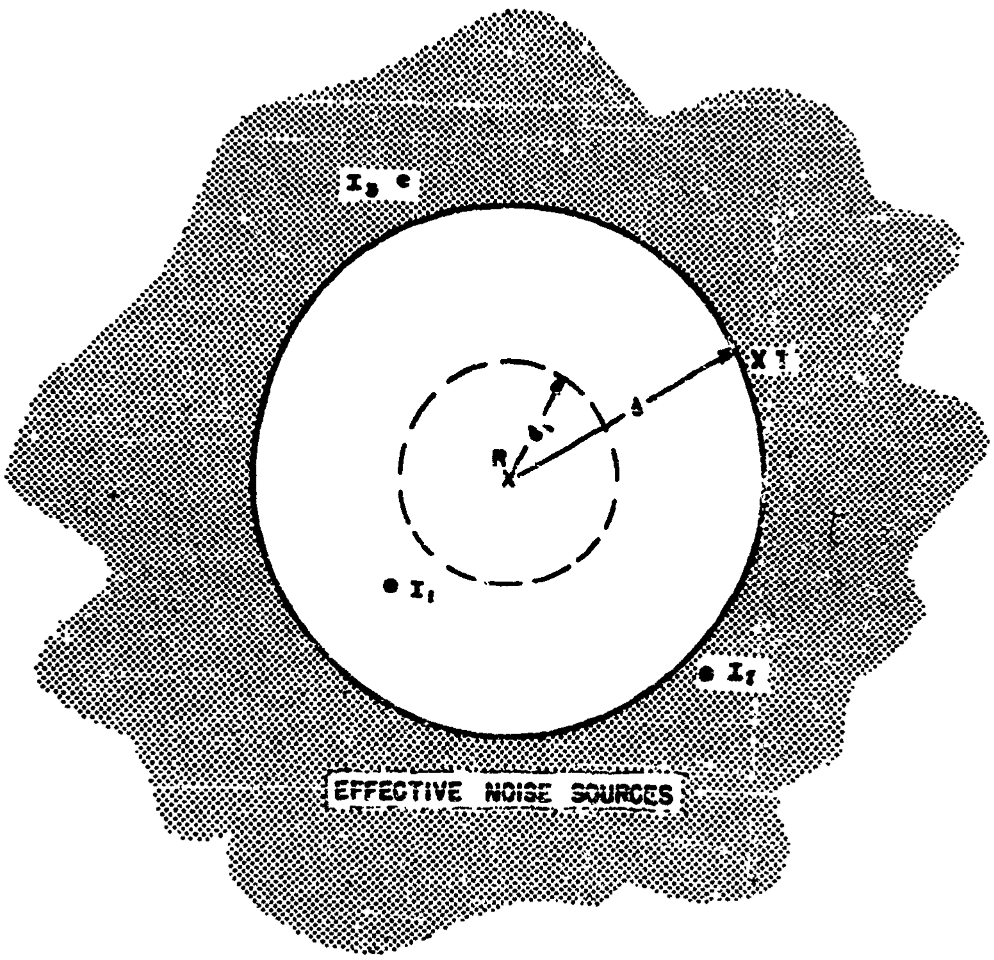

FIG. 2
RECEPTION UNDER ATMOSPHERIC NOISE CONDITIONS AND IN THE PRESENCE OF INTERFERING STATIONS

A-[illegible]-P-[illegible]

station at I_1 within the skip zone, transmitting near the signal frequency, does not produce any interference at the receiver. An interfering signal from a station at I_3 far beyond the skip distance is also relatively ineffective during daytime since the wave from it traverses a longer path within the D-region of the ionosphere, than the useful signal and so suffers greater attenuation. The contribution at the receiver, of noise sources at increasing distances beyond the edge of the skip zone also diminishes rapidly during daytime because of increasing attenuation. If the frequency of transmission is less than the maximum usable frequency, the signal-to-noise ratio decreases for two reasons. First, the emitted atmospheric noise power is larger at the lower frequencies. Second, the radius of the skip zone about the receiver is now smaller as indicated by the dotted circle in the figure. The number of effective noise sources and the number of possible interfering stations is thereby increased. The best signal-to-noise ratio is thus obtained when operating near the muf. Nighttime conditions are similar except that in the absence of attenuation the zone of effective noise sources and interfering stations extends indefinitely beyond the edge of the skip zone. In addition, muf's for nighttime transmissions are lower than those for daytime. Signal-to-noise ratios at night should therefore be smaller than those observed during the day. In this discussion of noise it was assumed that locally generated noise, including receiver noise, is of negligible intensity in comparison with atmospheric noise. This is usually the case for the communication system under discussion.

C SKY-WAVE TRANSMISSIONS IN THE LIAISON SYSTEM

When examining the sky-wave path between an aircraft and a ground station, the ionosphere may at first be assumed to be a perfect, spherical reflector for electromagnetic waves. Corrections can later be made, if necessary, for the various phenomena of ionospheric transmission neglected in such an analogy. Transmissions will usually take place near the muf so that in many cases only a single active path need be considered. In this case the transmission pathlength, D, and the radiation angle, θ, measured from the vertical, are simply related by the following equation:

$$\cot \theta \simeq \frac{H}{A} \cot \frac{D}{2HA} - \tan \frac{D}{4HA}. \qquad (5)$$

Here *H* is the fixed "virtual height" of the layer at which reflection is assumed to take place, *A* is the earth's radius, and *N* is the number of hops of the transmission path. This relationship is plotted in Fig. 3, for *E*-layer and *F2*-layer transmissions. It will be found that for large distances of transmission, considerable changes in virtual height of the layer cause only small differences in the radiation angle. Thus for a path length of 1800 km, a change in virtual height of the *F2*-layer from 250 km to 350 km changes the angle of radiation by only 5 degrees. For

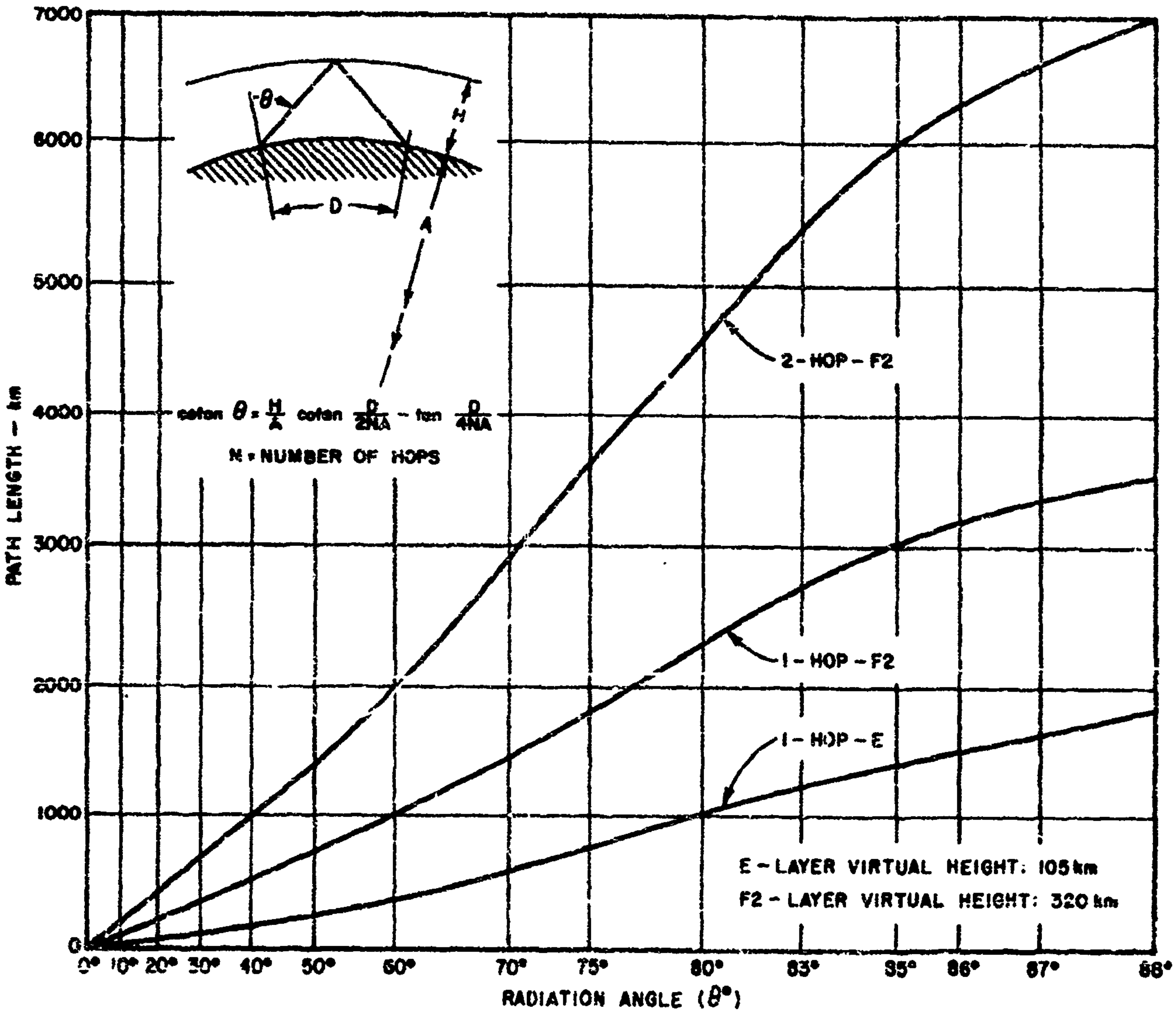

FIG. 3

LENGTH OF TRANSMISSION PATH AS A FUNCTION OF THE RADIATION ANGLE

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this reason no serious error in the radiation angle results from the assumption of a fixed height for the $F2$-layer.

The height of an aircraft above ground is small compared to the height of the ionosphere, especially when transmission via the $F2$-layer is involved. The relation between path length and radiation angle for transmissions between an aircraft and a ground station is therefore still essentially that given by Eq. (5) or Fig. 3. As shown in Fig. 4, however,

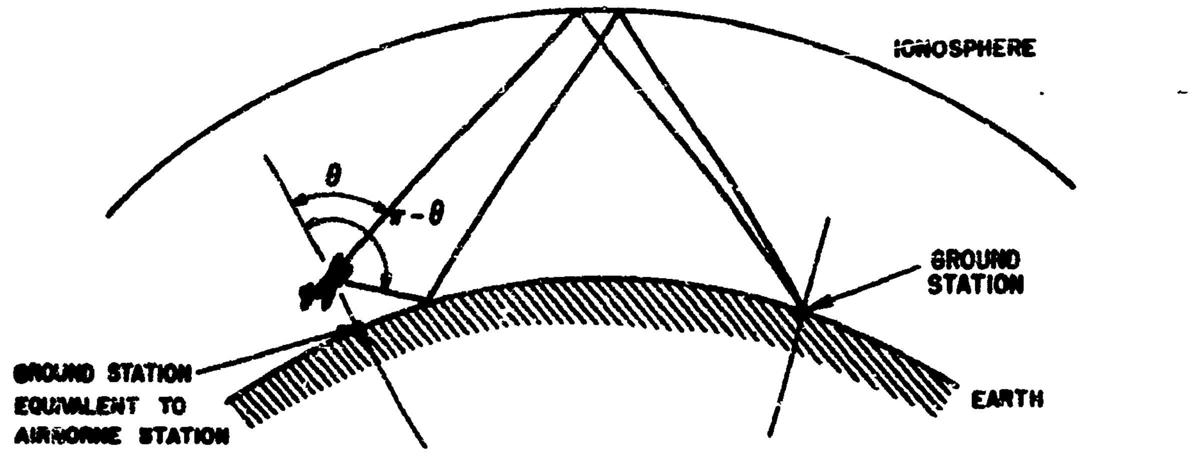

FIG. 4

SKY-WAVE TRANSMISSION BETWEEN AN AIRCRAFT AND A GROUND STATION

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radiation downward from the aircraft is reflected back to the ionosphere by the ground, and so contributes to the useful radiation. For practical purposes the ground reflected ray leaving the aircraft at an angle $(\pi - \theta)$ will reach the same receiver as the direct ray leaving at the angle θ, the error for an aircraft flying at a height h above the ground being less than h/B radians.

The actual ionosphere is not a smooth reflector, but rather has many irregularities which break up the sky wave into a large number of components, each of which is reflected from a slightly different point. The sky-wave field at the receiver therefore consists of many components of approximately equal field strength but in random phase. This is one of the causes of the continuous fading of sky-wave signals. The minute-to-minute variations of the field intensity is Rayleigh distributed. The direct wave and ground reflected wave transmitted from or received on the aircraft are also in random phase relationship, because of the scattering of the waves in the ionosphere and because of a similar process taking place at the ground reflection point. The total mean signal power is therefore proportional to the sum of the powers carried by the two separate rays. It follows from the random phase relationship between the direct and ground reflected rays that the height of the aircraft above ground will not appear as a variable in calculations of the received signal power. The station on the aircraft can thus be replaced by an equivalent station on the ground directly below it. The power radiated in any given direction by the antenna of this equivalent station is the sum of the powers radiated at the supplementary angles θ and $(\pi - \theta)$ by the actual airborne antenna.

The action of the earth's magnetic field on the sky-wave signal need not be considered here in detail. One consequence of this action, however, is of importance. Regardless of the polarization of the transmitted signal the received field is found to be elliptically polarized, with both orientation and aspect ratio of the polarization ellipse varying in a random manner. Thus, either horizontal or vertical polarization of the received wave is equally probable. The received power is then proportional to the sum of the powers radiated in two perpendicular directions of polarization.

The gain function of the ground antenna equivalent to the airborne installation can now be expressed in terms of the free-space gain, $G'(\theta,\phi)$, of the actual aircraft antenna. The quantities refer to the usual spherical coordinates about the aircraft, as shown in Fig. 5. The same coordinates are used for the equivalent antenna on the ground. This is justified because the height of the aircraft above ground is small compared to the height of the reflecting layer. Indicating gains for the two directions of polarization by subscripts, the gain of the equivalent antenna on the ground is given by

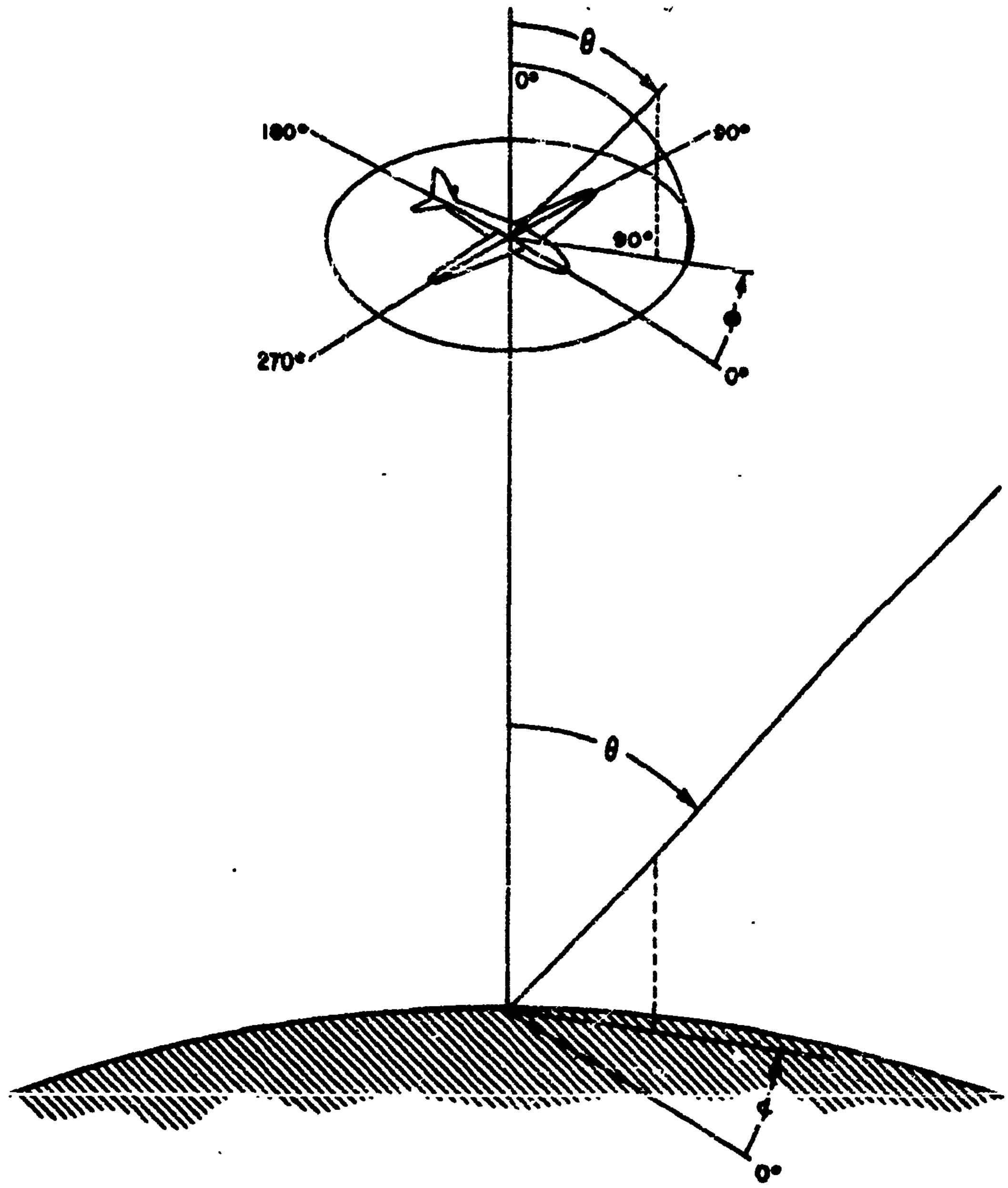

FIG. 5

COORDINATE SYSTEM FOR THE GAIN FUNCTION OF AIRCRAFT ANTENNAS

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$$G(\theta,\phi) = G'_\theta(\theta,\phi) + G'_\phi(\theta,\phi) + r_\theta^2(\theta)G'_\theta(\pi - \theta,\phi) + r_\phi^2(\theta)G'_\phi(\pi - \theta,\phi) \ . \quad (6)$$

The quantities r_θ and r_ϕ are the magnitudes of the ground reflection coefficients for the indicated polarizations. These coefficients vary, of course, as the aircraft flies over different types of terrain. It was

found that no serious error results when r_θ and r_ϕ are both taken to be unity.

It will be shown in the next chapter how the relation between virtual layer height and vertical angle about the aircraft shown in Fig. 3, and the gain function of the equivalent antenna on the ground, lead to an estimate of those vertical angles about the aircraft which are useful for liaison transmissions.

D. THE ROLE OF THE AIRBORNE ANTENNA IN RECEPTION ON THE AIRCRAFT, AND TRANSMISSION FROM THE AIRCRAFT

It was found experimentally* that the preponderant noise in the liaison system is atmospheric noise. The noise at the receiver therefore depends on the strength of the noise field at the receiving site and the gain of the receiving antenna in the direction of the noise sources. If transmissions take place from the aircraft to the ground the signal-to-noise ratio at the receiver will depend on the power radiated by the aircraft antenna in the direction of the receiver. On the other hand, if the receiver is located in the aircraft, it is the relative gain of the antenna in the direction of the transmitter compared to the gain in the direction of the noise sources which determines the signal-to-noise ratio, both the signal and noise fields being of course independent of the antenna.

As an illustration, consider the two hypothetical radiation patterns of Fig. 6. If these two antennas are used for transmitting, the signal-to-noise ratio at the receiving station will be larger in Case (b) than in Case (a), in proportion to the ratio of the gains of the major lobe of the pattern to that of the minor lobe. In receiving, however, when atmospheric noise arrives over the indicated sector, the signal-to-noise ratio may be less in Case (b) than in Case (a). The received signal is, of course, still larger for Case (b). The increased amount of noise received over the major lobe, however, compared to that received over the minor lobe may more than offset this gain in signal power.

The signal-to-noise ratio depends on the relative locations of noise sources, the receiver, and the transmitter. For a fixed point-to-point link it is often possible to adjust the gain of the receiving antenna so

* See Appendix D.

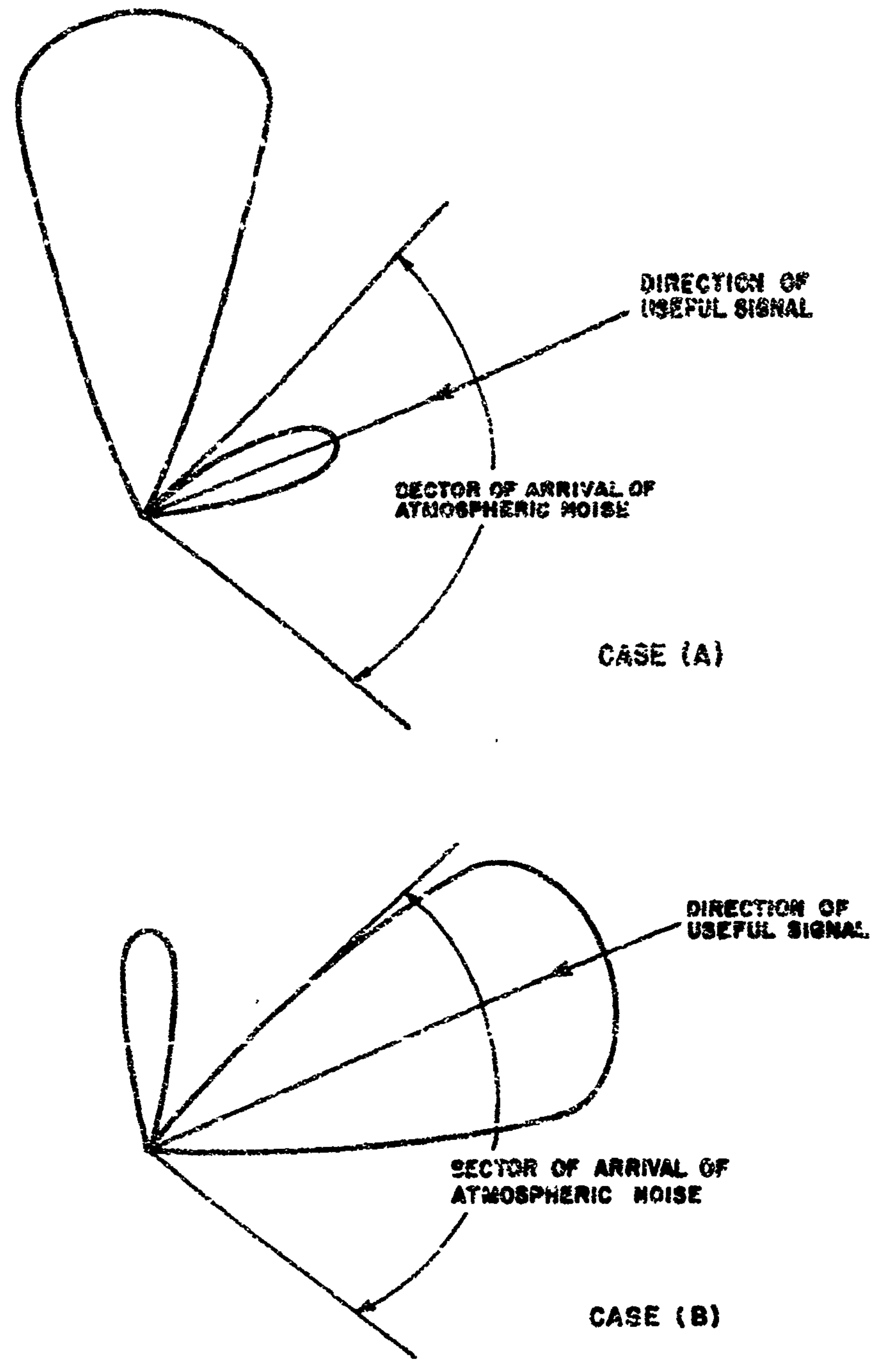

FIG. 6

THE ROLE OF THE RADIATION PATTERN IN TRANSMITTING AND RECEIVING UNDER ATMOSPHERIC NOISE CONDITIONS

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that maximum gain is obtained in the direction of the signal, with nulls or minor lobes in the principal noise directions This is usually not possible in the liaison system, especially when receiving on the aircraft. The signal may arrive anywhere within a large azimuthal sector about the aircraft and it certainly would not be practical to alter the heading of the aircraft in order to obtain the best signal-to-noise ratio. When receiving on the ground, the direction of arrival of the signal is also usually distributed over a large azimuthal sector. For some ground stations, however, the azimuthal angle of arrival of transmissions from the aircraft may be preponderantly in one or two directions. In these cases careful design and orientation of the ground station antenna may produce substantial gains in signal-to-noise ratio.

In general, it has been found that differences in the gain of aircraft antennas are of more importance in transmitting than in receiving. This might be surmised from the fact that the signal-to-noise ratio in receiving is determined by a much larger portion of the pattern than when using the antenna for transmitting. A detailed analysis of the signal-to-noise ratio at an airborne receiver under atmospheric noise conditions will be found in Appendix D.

E. ELECTRICAL LIMITATIONS OF H-F AIRCRAFT ANTENNAS

The wavelengths used for liaison communications are of the same order of magnitude as the dimensions of the aircraft. The fuselage of a C-54 transport, for example, is about one wavelength long at a frequency of 10 Mc. The h-f antenna will excite currents on the skin of the airframe, which will go into resonance at frequencies determined by the various natural resonances of the aircraft structure.

The close connection between the electrical properties of the h-f antennas and the aircraft structure is well illustrated by the behavior of the input resistance of tail-cap antennas on different types of aircraft. Figure 7 shows resistance data for five different aircraft. The resistance is plotted as a function of the length of a particular path on the airframe, divided by the wavelength. The path length used is that from one wingtip to the wing root and back along the fuselage and dorsal fin to the tip of the vertical stabilizer. The actual path length on the five aircraft varied from about 85 ft to 130 ft. It is clear that the first anti-resonance for each of the antennas occurs when this path corresponds to about a half-wavelength. If a wing cap were used instead of a

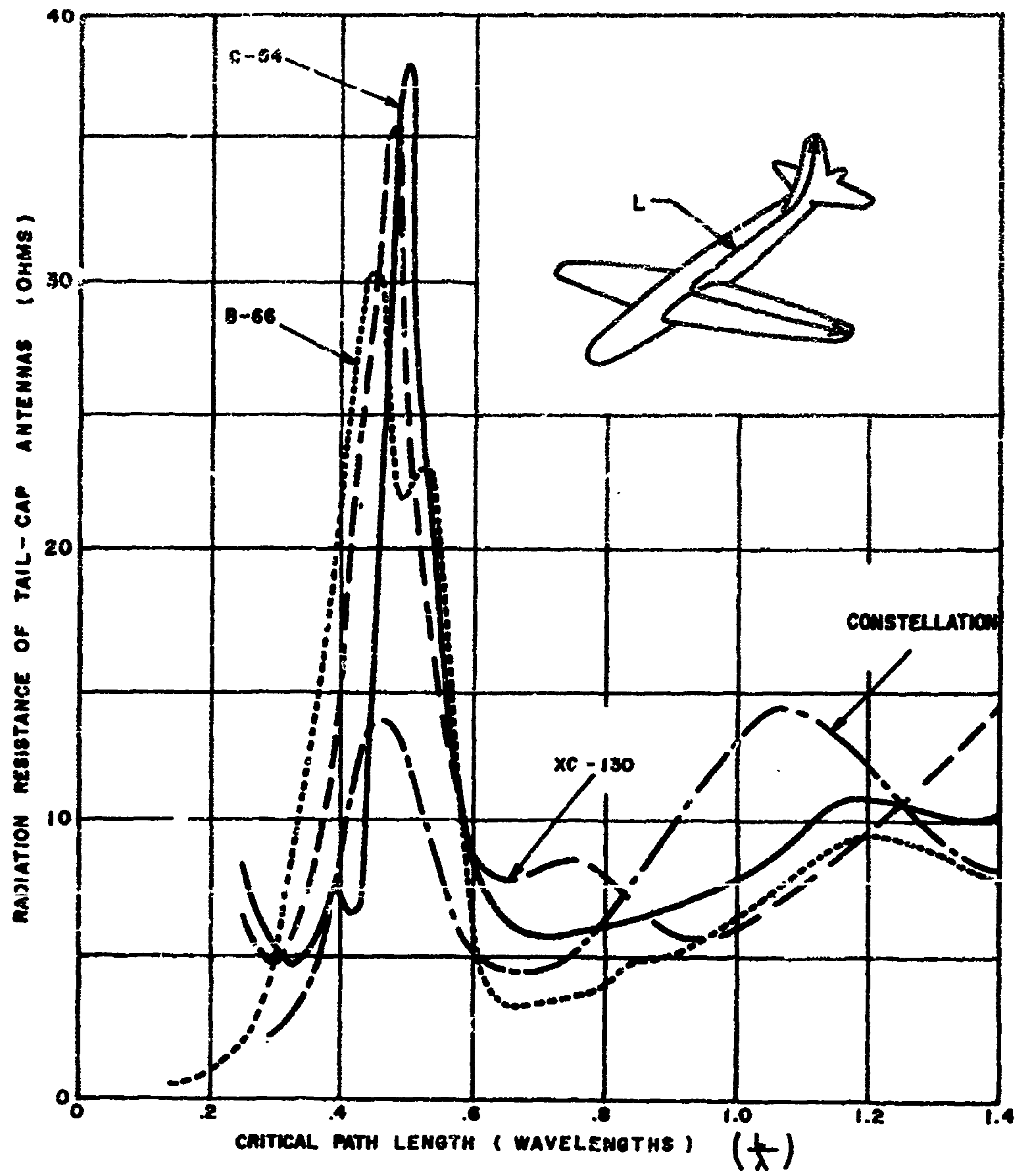

FIG. 7

RADIATION RESISTANCE OF TAIL-CAP ANTENNAS

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tail cap, the same resonant peak of the input resistance would be found although it might no longer be the first anti-resonant point reached by the antenna impedance.

As the frequency is raised beyond the range shown in Fig. 7, other path lengths become resonant. These depend to a larger extent on the particular aircraft than the resonance illustrated in the figure. However, the same resonant modes are often excited by different antenna structures on a given type of aircraft.

Obviously, not every antenna excites all these modes. A tail-cap antenna, for instance, can bring only half a wing into resonance since it cannot cause current to flow symmetrically on both the left and the right wing. On the other hand, the first anti-resonant peak of the impedance of a wing-cap antenna usually occurs when the wing span is a half-wavelength long. Fixed wire antennas resonate at multiples of half-wavelengths of the wire itself as well as at the various resonant points of the airframe. All these possible resonant modes on an aircraft are due to critical path lengths which, while not identical, are all of comparable magnitude. The general structure of the impedance function for the various antennas therefore tends to show marked similarities.

The radiation patterns of the antennas also show similarities since they are directly related to the current distribution. The details of the patterns depend on the particular antenna. As will be seen presently, however, the quantity of interest is an average of the gain function over a large solid angular sector. It is this average which tends toward uniformity for all possible h-f antennas on a given type of aircraft. Important differences still do exist. As was seen earlier, useful radiation should be directed towards the horizon, while upward and downward radiation does not contribute to the type of communication desired here. The vertical tail fin is the only part of the usual airframe on which currents will produce the required kind of radiation pattern. A tail-cap antenna is therefore often found to be a better radiator than a wing cap, for instance, since the wing cap excites currents on the vertical stabilizer to a much smaller degree.

At the lower end of the high-frequency band, all airframe dimensions are small in terms of the wavelengths. Almost any antenna system which might be employed will then have the radiation pattern of a small linear dipole. The orientation of this pattern with respect to the airframe will depend,

of course, on the particular type of antenna element employed. When the gain function is averaged over a solid angle sector, however, these differences usually produce negligible differences in the measure of pattern effectiveness.

It is apparent from the above discussion that, in general, differences between several possible well-engineered h-f aircraft antennas tend to be small in comparison with variations in other parts of the system such as the transmission path. The rating of antennas should therefore be based on the performance of those communication links for which these small differences are of the greatest importance, that is on cases where the reliability of the system is likely to be marginal. For this reason, major emphasis in the antenna system evaluation has been placed on transmissions from the aircraft over the longest distance ranges involved.

F. INTELLIGIBILITY OF SPEECH TRANSMISSION OVER THE LIAISON SYSTEM

The sole task of the h-f liaison system is the transmission of specific types of intelligence from or to an aircraft. This intelligence is usually conveyed by spoken words. Because of fading and noise, some of the words of a message may no longer be recognizable at the receiver. A count of the words of a message which are correctly understood at the receiver provides a significant measure of the performance of the communication system. The fraction of the transmitted words which is identified at the receiver is called the articulation score and has long been used to measure the effectiveness of voice communication circuits.[1]

Because of the direct significance of articulation scores to the overall performance of a communication circuit, the effect of the aircraft antenna on the performance of the liaison system should be evaluated on the basis of such scores. Before such an application can be made, however, a discussion is in order, of the methods employed to obtain articulation scores and of the variables which influence their values.

In an articulation test a talker pronounces selected speech items. These are transmitted over the circuit and a listener at th. receiving end records the sounds that he hears. The number of words correctly identified

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[1] Harvey Fletcher, *Speech and Hearing*; D. Van Nostrand Co., Inc.; 1929.

by the listener depends on the peculiarities of the circuit used, and in particular on the noise and distortion introduced by it. These are usually the qualities of the system we wish to evaluate. Articulation scores also depend upon a large number of subjective factors which enter as a parameter in every test. For example, the announcer introduces such variables as vocal quality, regional pronunciation, proper or improper use use of microphones, and other individual characteristics. Listeners differ from each other in their ability to comprehend words under difficult conditions, in concentration on the task they are to perform, and so on. It becomes obvious, therefore, that the results of measurements of articulation cannot be interpreted in absolute terms. Articulation scores are relative scores contingent on the use of specific announcers, listeners, and equipment. All comparisons of communication devices should be made with conditions kept as uniform as possible. The quantity of significance is the change in articulation score resulting from a controlled variation of one parameter or one device of the system.[1]

The signal-to-noise ratio at the receiver is the most important quality on which articulation scores depend, at least for the application of articulation tests considered here. A typical form of this relationship is shown in Fig. 8. There is an upper limit of signal-to-noise ratio above which almost all words are correctly identified, and a lower limit below which none can be heard correctly. Between these two, the articulation score is an approximately linear function of the logarithm of the signal-to-noise ratio. The limits of 0% and 100% articulation, and hence the slope and position of the linear part of the curve depend on the vocabulary used for the tests and the type of noise mixed with the signal.

The vocabulary used for articulation tests greatly influences the articulation scores observed over a voice communication link. This is illustrated in Fig. 9. This figure is a plot of the relative intelligibility of a voice transmission circuit in the presence of noise, with the number of possible words in the vocabulary as a parameter. The curves show the average percentage of words correctly received by a group of listeners as a function of the signal-to-noise ratio in decibels for vocabularies limited to 2, 8, 32, 256, and 1000 words. The curve for a 2-word vocabulary represents simply an on-off type transmission, and might be

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[1] J. P. Egan, Articulation Testing Methods, OSRD Report No. 3802, 1 November 1944; Psycho-Acoustic Laboratory, Harvard University.

interpreted as the equivalent of tone telegraphy over this circuit. The 1000-word vocabulary is representative of the results which would be obtained if no restrictions were placed on the choice of words by the operator. The curve for the 32-word vocabulary is very nearly the result which would be observed for words restricted to the phonetic alphabet.

Let us compare transmissions employing only the phonetic alphabet, with transmissions in which there is virtually no restriction of the vocabulary employed,[1] i.e. the curves for a 32-word vocabulary and a 1000-word vocabulary of Fig. 9. For sufficiently high signal-to-noise ratios, say above +12 db, there is no significant difference in intelligibility between the two transmissions. As the signal-to-noise ratio is progressively deteriorated, however, the curves illustrate that the percentage of words correctly received decreases rather rapidly if the vocabulary is unrestricted. On the other hand, for a vocabulary corresponding approximately to the phonetic alphabet. there is no significant deterioration of intelligibility until the signal-to-noise ratio approaches 0 db. In the case of the 1000-word vocabulary, only 35% of the words are correctly received for a signal-to-noise ratio of 30 db, while 95% of the 32-word vocabulary can still be identified.

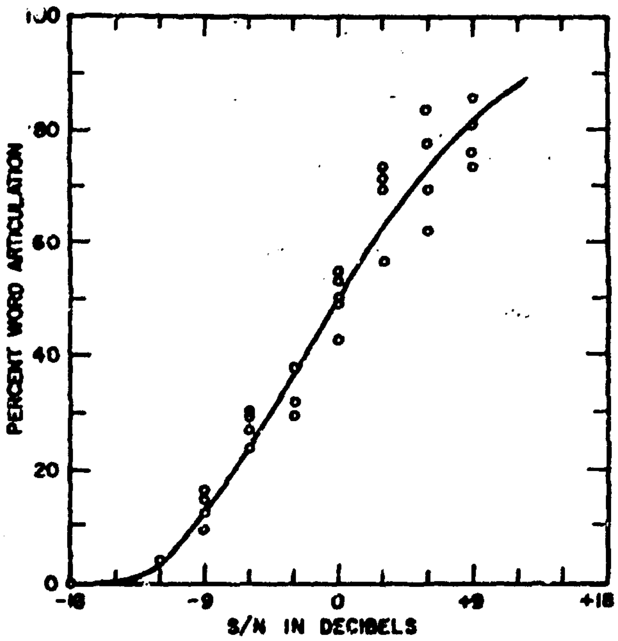

FIG. 8

WORD ARTICULATION FOR CONTINUOUS SPEECH HEARD IN THE PRESENCE OF CONTINUOUS NOISE

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FROM MILLER AND LICKLIDER, JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA, 22, 171, (MARCH [illegible])

This data can be interpreted in another way. Suppose it is necessary to maintain 60% intelligibility. With an unrestricted vocabulary an average signal-to-noise ratio of +9 db would be required. If the operator is

[1] See J. V. N. Granger's presentation and subsequent discussion reported in "Airborne Radio Equipment Symposium," Chapter I, International Air Transport Association, Copenhagen; 1952.

restricted to the use of the phonetic alphabet the same intelligibility is obtained with an average signal-to-noise ratio of only -9 db. In other words, a power loss of 18 db can be tolerated by the system if the vocabulary is restricted to a phonetic alphabet. From these data it is obvious that when communication is suffering from adverse noise conditions, it is extremely important for the maintenance of the highest degree of intelligibility, that the operators conform rigorously to standard operational procedures and standard vocabularies. Any deviation from these inevitably results in decreased intelligibility.

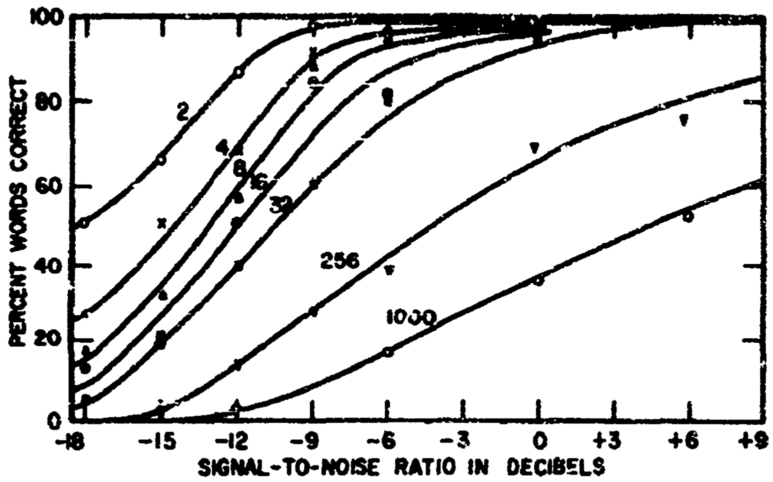

FIG. 9

THE INFLUENCE OF THE VOCABULARY ON WORD ARTICULATION FOR NOISY CHANNELS

A-60SC-F-290

FROM MILLER, JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA, 22, 723, (NOVEMBER 1950)

Sky-wave transmissions introduce another factor which strongly influences the intelligibility of speech transmitted over the system. Because of interference of the many components into which a signal is broken up by the ionosphere, the signal strength at the receiver is constantly changing. This is known as fading and it is always present in varying degrees when utilizing high-frequency communication systems. Two types of fading have already been discussed; that due to changes in the direction of polarization caused by the action of the earth magnetic field on the ionosphere, and fading due to irregularities in the state of ionization in the layer utilised for transmission. These are the most common types of fading. The fading rate on long distance h-f circuits due to these causes are seldom more rapid than one fade in every two seconds. More rapid rates of fading occur when ionospheric conditions are disturbed, and in areas where both ground and sky wave can be received simultaneously. The effect of fading on speech transmission is illustrated in Fig. 10. These curves show the articulation scores observed as noise is switched on and off at a cyclic rate given by the abscissa. The noise was on half of the time, and off half of the time during each cycle. The signal-to-noise ratio during the time when the

noise was on is the parameter for the different curves. It is apparent from these curves that for the low fading rates common in the h-f circuit, the intelligibility is nearly the average articulation score which would be predicted from the relationship giving these scores as a function of signal-to-noise ratio in continuous noise, such as shown in Fig. 8. As an example, consider a signal-to-noise ratio of 0 db. From Fig. 8 it is found that about 50% of the words would be heard correctly for such a signal-to-noise ratio and continuous noise. For the interrupted noise, the signal-to-noise ratio is 0 db half of the time, and very large for an equal interval of time. The average articulation score for the interrupted signal, as predicted from observations using continuous noise is therefore given by

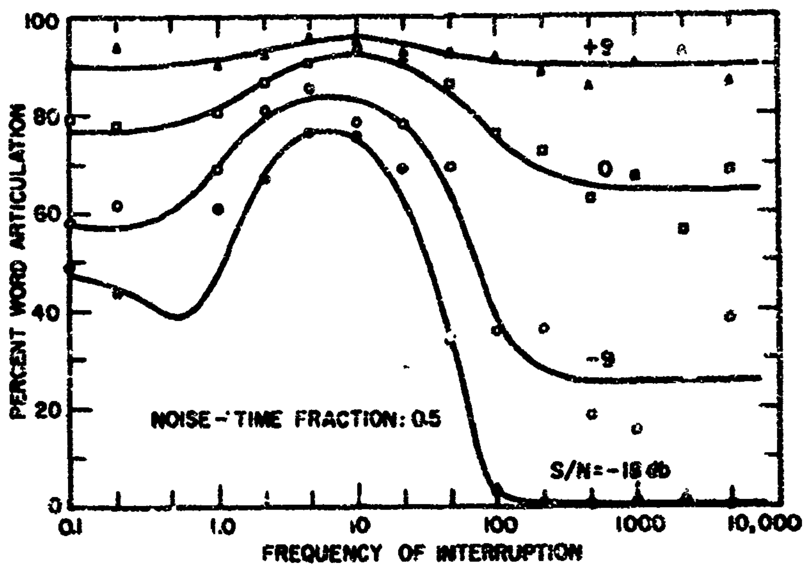

FIG. 10

THE MASKING OF CONTINUOUS SPEECH BY INTERRUPTED NOISE

A-ROSC-F-2N

FROM MILLER AND LICKLIDER, "THE INTELLIGIBILITY OF INTERRUPTED SPEECH"; THE JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA, 22, 169, (MARCH 1950)

$$\frac{50 + 100}{2} = 75\% .$$

This is very nearly the score shown for the $S/N = 0$ db curve of Fig 10 for frequencies of interruptions less than one every three seconds. As explained below, average articulation scores will form the basis of comparison of different aircraft antennas for the liaison system. The above example shows that the use of this concept is justified when the signal-to-noise ratio is subject to fading.

More rapid fading rates such as those observed during ionospheric disturbances usually cause more serious deterioration of articulation scores than would be predicted from simple averaging. Such cases are fortunately rare, and are therefore not considered here. In any case, the

reduction of loss in intelligibility caused by fading is wholly outside the capabilities of aircraft antenna design. System improvements may be achieved by resorting to different modulation techniques and by changes in operational procedures. Such considerations are outside the scope of the present discussion.

It should be pointed out that the effects of fading illustrated in Fig. 10 should be taken in a qualitative sense only. These results are based on a cyclic on-off switching of noise, quite different from the random changes in signal-to-noise ratio observed for the sky-wave signal and atmospheric noise. As shown in Appendix E, however, by actual experiment, the effects of ordinary fading are essentially those predicted from the curves shown here.

Another type of fading which should be briefly mentioned is due to selective phase and amplitude changes of the different frequency components of the signal, and it is therefore known as selective fading. Such fading can produce very severe distortion of the signal, an effect fortunately observed only infrequently. Selective fading has been studied in the past[1] and is still under intensive investigation. While such an analysis may lead to ways and means of counteracting the effects of selective fading, these methods will certainly not involve the design of the aircraft antenna.

The effects of fading on articulation scores can be illustrated in another fashion. In Fig. 11 two curves are presented, giving the articulation score as a function of the median signal-to-noise ratio. The first of these, labeled "White Noise," was measured in the laboratory using standard word lists consisting of 50 monosylabic words. Uniform continuous noise of known power level, such as might be obtained from a noise diode, was mixed with the signal. The scores plotted represent the average of the scores observed by a group of six listeners. It is seen that for these tests an increase of about 13 db in signal-to-noise ratio is required to bring the circuit from a point where hardly any of the words can be understood, to a condition where practically all words are correctly identified.

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[1] R. K. Potter, "Transmission Characteristics of a Short Wave Telephone Circuit," Proc. I.R.E., Vol. 18, pp. 581-648; April 1930.

The second curve, labeled "Normally Fading Sky-Wave Signal," shows the articulation scores observed when the same words are transmitted over a long distance high-frequency circuit. While the noise here is atmospheric noise rather than the white noise of the previous tests, the difference between the two curves is due mainly to fading. For the white noise the median signal-to-noise ratio and the instantaneous signal-to-noise ratios are practically the same. For sky-wave transmission, however,

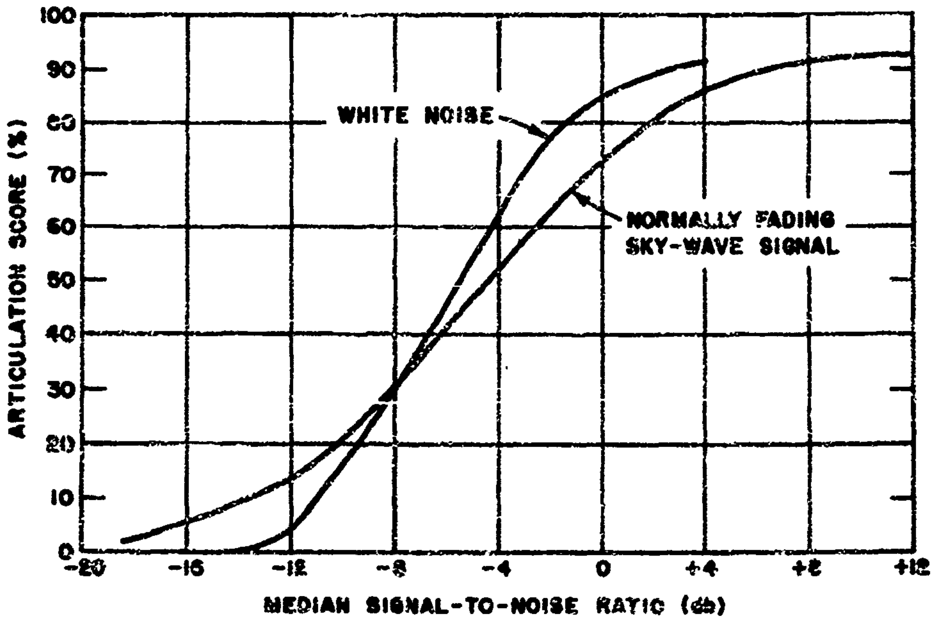

FIG. 11

ARTICULATION SCORES AS A FUNCTION OF THE SIGNAL-TO-NOISE RATIO FOR WHITE NOISE, AND FOR A NORMALLY FADING SKY-WAVE SIGNAL IN ATMOSPHERIC NOISE

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the instantaneous values may differ by 10 db or more from the median signal-to-noise ratio. Some of the transmitted words are therefore heard under much more favorable conditions than indicated by the median value of the signal-to-noise ratio, others under much worse circumstances. As a result, the change in signal-to-noise ratio required to improve the circuit from very poor intelligibility to almost perfect intelligibility is increased in comparison with that required in white noise. The range in signal-to-noise ratio is about 25 db as compared to 13 db in the previous case. This range of signal-to-noise ratio defines the region where the reliability of the system is marginal, that is, within this range the

system is neither perfect nor useless. The chance of having to operate within the marginal range of reliability is therefore seen to be about twice as high for h-f transmissions as they would be for a v-h-f system, for instance, where fading does not occur and where the controlling noise originates in the front end of the receiver. In fact, one may expect that a large percentage of high-frequency transmissions must take place under conditions of marginal reliability, so that an evaluation of antenna systems under these circumstances is fully justified from this point of view, as well as from those previously mentioned.

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CHAPTER 5

CRITERIA FOR THE EVALUATION OF H-F AIRCRAFT ANTENNA SYSTEMS*

A. INTRODUCTION

In the preceding chapters the behavior of the entire h-f liaison system was discussed and a description was given of the way in which it is used for long distance air-to-ground and ground-to-air communications in the Air Force. We must now establish means by which the effect, on the system, of the airborne antenna can be evaluated in a quantitative fashion. Such performance measures must not only be based on the electrical parameters of the antenna system but should be restricted to those quantities which can be measured or estimated from tests on models of the aircraft and of the aircraft antenna.

It is more convenient to evaluate aircraft antennas on a relative basis. One antenna system is chosen as a reference and the performance of other antennas for the same type of aircraft is expressed in terms of the performance of the reference system. There are several reasons for choosing such a scheme rather than an absolute measure for the worth of an antenna system. The overall system performance depends to a very much larger degree on the conditions of the ionosphere than on the particular choice of antennas. This tends to mask the factors which are to be measured. Furthermore, the size of the aircraft places a limit on the capabilities of any high frequency antenna system which might be designed for it. An absolute performance standard is therefore of no particular significance insofar as the design of a suitable antenna for a particular type of aircraft is concerned.

It has already been stated that a significant way to rate antennas is to ascertain their effect on the intelligibility of speech transmitted over the system. Articulation scores are therefore chosen here as the primary measure of the performance of the liaison system. Such a scheme leads, of necessity, to a relative rating of antennas since articulation

* The discussions in this chapter are based on the derivations and results presented in Appendix B.

scores have a meaning only in this sense. Of course the measures of antenna system performance which are to be established should not require articulation tests over the completed system. The "voice intelligibility index" which is discussed later is a rating scheme which fulfills these requirements. It involves only the electrical parameters of the antenna system and it is closely related to articulation scores. If two antenna systems have equal intelligibility indices, the articulation scores which would be observed over the systems would also be the same, if observations were carried out during a sufficient length of time. Single articulation tests will measure the effectiveness of one particular air-to-ground link. A comparison of antennas must therefore be based on the average of the articulation scores which would be measured over all possible such links.

For h-f aircraft antennas, ratings based on the voice intelligibility index are almost equivalent to those arrived at by a much simpler measure — the antenna system efficiency. The latter is therefore recommended as a practical measure of h-f aircraft antenna system performance.

Another scheme for rating antennas — the radiation pattern distribution function — was also considered. It has been used in the past for the evaluation of antennas for v-h-f and u-h-f systems. This measure depends critically on the ambient noise level which in the h-f system varies over a considerable range. The radiation pattern distribution function is therefore less suited for the comparison of antennas for the liaison system than the voice intelligibility index or the antenna system efficiency.

All the proposed measures of antenna performance are functions of the signal-to-noise ratio at the receiving end of the communication link. The noise of interest here is atmospheric noise. The signal strength depends on the antenna gains, the efficiency of power transfer between the transmitter and space, and on the total amount of power available at the transmitter. Both signal and noise are also subjected to all the variations caused by changes in ionospheric conditions. Although the antenna evaluation is based on tests performed in the laboratory, account must be taken of this dependence of liaison transmissions on the ionosphere.

As explained earlier, differences in aircraft antenna systems bring about much larger changes in system performance when a signal is transmitted from the aircraft than when transmitting from a ground station and receiving in the air. In addition, the amount of radio frequency power available from airborne equipments is much smaller than the power which

can be radiated by a ground station. For these reasons the rating schemes will be discussed for transmissions from the aircraft to the ground.

B. THE DEPENDENCE OF H-F ANTENNA EVALUATION ON THE IONOSPHERE AND ON THE DISTRIBUTION OF GROUND STATIONS

The h-f antenna on a given aircraft will be used for a large number of communication links differing among each other in the orientation of the transmission path with respect to the aircraft, in the distance between the two ends of the link, and in frequency of transmission. It is apparent that a meaningful evaluation measure must take into consideration the system performance for all these different conditions. A convenient way to accomplish this is to find the average performance for all the cases. Since not all of these occur with equal likelihood, the averaging must be a weighted one. The weighting function expresses the probability that a given communication link will be established at some time during the life span of the system.

Changes in ionospheric conditions with the time of day, with the season, with the sunspot cycle, and with the geographical location of the transmission path profoundly influence the performance of the liaison system. Further averaging of the evaluation scheme over these coordinates is therefore required in order to obtain a representative measure. A system for antenna evaluation which takes detailed account of the influence of the ionosphere is presented in Appendix C. It is shown there that considerable simplifications are justified in practice. Both signal and noise can be taken as a constant for a given orientation of the transmission path. Noise will be considered as a parameter of the evaluation function so that a study can still be made of the effect of changing noise levels on the antenna ratings. The signal strength is assumed to depend only on the amount of power radiated from the aircraft, in the proper directions for reception at a given ground station. It is therefore proportional to the aircraft antenna gain in these directions and to the efficiency of power transfer between the transmitter and space. Signal strength, of course, also changes with the path length of transmissions. Variations in ionospheric conditions, however, cause variations in the signal strength many times larger than those due to free-space signal attenuation with increasing distance from the transmitter. More important when making a comparison of the evaluation factors for different antenna systems, the factors involving signal attenuation due to the length of the

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transmission path are found to be almost the same for all antennas and so do not affect the relative rating of antennas The decrease of signal strength with increasing path length will therefore be neglected.

In addition to the changes in signal-to-noise ratio which take place over periods of an hour or more, variations in signal to-noise ratio of short time periods, which are known as fading, are observed. It is found that most of the fading is due to changes in signal strength rather than to changes in the strength of the atmospheric noise field. When a receiver with automatic volume control is used, which is usually the case, the signal strength at the output of the receiver will be almost constant On the other hand, for every decrease in the signal field strength there is a corresponding increase in the gain of the receiver and hence an increase of the output noise The variations in signal-to-noise ratio at the receiver output will therefore be practically the same as those at the input of the receiver. The variations of signal power at the input are transformed to opposite variations in noise level at the output. These variations usually occur at a rate of, at most, about one every two seconds. While this type of fading does alter articulation scores in the way explained earlier, it can be shown that the relative performance rating of several antenna systems is not affected by it. Fading can therefore also be neglected when defining our performance criteria.

The variation of ionospheric conditions with time is not the only property of sky-wave transmission which bears on the problem of antenna evaluation. The vertical angle at which a signal leaves the aircraft also depends on the ionosphere as well as on the distance of transmission. If the transmission mode of the signal path is known, that is, if the ionospheric layer used for the transmission and the number of hops required are known, the vertical angle and the distance are functionally related as shown by Eq. (5). The distance of transmission over which the liaison system must operate depends on the type of service in which the aircraft using the system is employed Some of these distances will be used more often than others during the life span of the type of aircraft for which the antenna is being designed. Or in other terms, the distances of transmission will have a statistical distribution. A change of variables will lead to a distribution of useful vertical directions about the aircraft, provided the ionospheric transmission modes are known. One cannot state in absolute terms whether or not a given vertical angle may at some time be used for liaison transmissions; what is known is the probability that it will be used for such transmissions

For long range transmissions, that is, those over distances of more than about 1300 mi., $F2$-layer modes are far more frequent than propagation via the E-layer. Furthermore, when operating near the muf, the number of hops for the path is the minimum possible number for the distance range involved. With these assumptions and the further assumption of a fixed virtual height for the $F2$-layer, the probability distribution of transmission path lengths can be uniquely transformed into the probability distribution of useful vertical directions about the aircraft. Such a procedure is carried out in Appendix C It is shown there that the details of these distribution functions do not greatly influence the relative rating of different antennas. In practice therefore, it is permissible to take the probability distribution of vertical angles about the aircraft as uniform over a vertical sector considered useful for transmissions, and zero for all other vertical directions

It was pointed out in the previous chapter that in evaluating the system performance, maximum emphasis should be placed on transmissions over the longest distances involved For bombing missions the important range of path lengths extends from about 1500 km to 5000 km. According to Fig. 3, this involves radiation angles larger than 70 degrees for ground based antennas. On the other hand, propagation paths of more than the minimum number of hops may sometimes be of importance, as well as transmissions over distances somewhat shorter than 1500 km. The vertical sector about the aircraft, considered as useful for liaison communication, will here be taken as extending from 30 degrees above the horizontal plane through the aircraft, to 30 degrees below this plane, (i.e. from $\theta = 60$ degrees to $\theta = 120$ degrees in Fig. 3). Angles below the horizon must of course be included to allow for the ground reflected rays as explained in connection with Eq. (6). It is shown in Appendix B that antenna ratings do not critically depend on the exact extent of the useful vertical sector.

Useful directions in azimuth about the aircraft depend only on the way in which ground stations are distributed about the aircraft during all the missions for which it is to be used. For bombing operations, all azimuthal directions of transmission from the aircraft are equally likely to occur. The useful angular sector in azimuth therefore includes all these directions about the aircraft. For aircraft used in the transport service, the forward and rear quadrants about the aircraft usually contain the transmission path much more frequently than do the side quadrants. The useful sector in azimuth for those applications may then be restricted to the forward and rear quandrants.

The performance of aircraft antennas will be different at different frequencies. Hence, an additional averaging of the performance measure over the frequency range is required, suitably weighted with respect to the relative number of times each of these frequencies will be used. It was found, however, that all frequencies between 6 Mc and 24 Mc are almost equally probable to occur as maximum usable frequencies for paths and distances of transmissions of interest here because of the large variations in muf which take place with the changing period of the sun spot cycle. The performance measures will first be presented as functions of frequency. A simple, unweighted, averaging over frequency of the performance measure will then provide an overall evaluation of the antenna systems.

Frequencies below 6 Mc will, in general, be used for transmissions over paths of shorter length than those of interest here. Performance of the system at that end of the band must nevertheless be considered. The sun spot cycle at present, is approaching its minimum. Consequently, during the next few years the useful high frequency spectrum will be sharply reduced. During this restricted period of time, frequencies between 2 and 4 Mc may be used more often for the long range transmissions than those above 18 Mc. Apart from this, the low end of the band will always be required for some liaison system use, regardless of the sun spot number. Adequate system performance over the low end of the high-frequency band is therefore a definite requirement. The electrical properties of the aircraft antennas are sufficiently different at the low end of the band, however, to permit a simplified evaluation procedure there. This is discussed in the following chapter.

C VOICE INTELLIGIBILITY INDEX

The intelligibility of a communication link, as measured by articulation scores, is a function of the signal-to-noise ratio at the listeners' ears. Typical examples of this relationship are shown in Figs. 8, 9, and 11. The signal is assumed to depend only on the power radiated in the direction of the receiver. It is therefore proportional to the gain of the aircraft antenna, to the total available power at the transmitter, and to the fraction of this power which is actually radiated into space. As discussed above, the noise will be taken as a parameter. It will be more convenient to express signal-to-noise ratios in decibels. If P_t is the total available transmitter power, P_r the total power radiated by the antenna, and $G_r(\Omega)$ the gain of the equivalent antenna on the ground, as given by Eq. (6), in the direction of the solid angle Ω, the signal strength in decibels is:

$$g'(\Omega) = 10 \log_{10} KP_t\left(\frac{P_r}{P_t}\right)G(\Omega) \ . \tag{7}$$

The factor, K, transforms the radiated power into signal power at the output of the receiver. Under our assumptions it is a constant for all systems under consideration. The same is, of course, true for the total available power P_t. Let us therefore write Eq. (1) as.

$$g'(\Omega) = C + 10 \log_{10} \eta_{tr} G(\Omega) = C + g(\Omega) \ , \tag{8}$$

where, $C = 10 \log_{10} KP_t$, is a constant for all systems which are to be compared. The ratio

$$\eta_{tr} = \frac{P_r}{P_t} \tag{9}$$

is the power transfer efficiency between transmitter and space as defined in Eq. (2). It accounts for ohmic losses of the antenna systems, and for the apparent loss of power due to incomplete matching of the antenna to the transmitter. The power transfer efficiency depends on the frequency and is obviously independent of the spacial coordinates about the aircraft. The function $g(\Omega)$ may be considered as the effective gain of the equivalent antenna on the ground.

The noise level, y, is to be a parameter which can assume any desired value. The constant, C, of Eq. (2) can therefore be absorbed by it and the signal-to-noise ratio in decibels can be written as

$$g(\Omega) - y \ . \tag{10}$$

For any fixed value of y and a given direction of the transmission path with respect to the aircraft, the articulation score which would be observed over the system can then be determined from the curves of Fig. 8 or similar curves. Using a linear approximation to these curves and letting d be the range of signal-to-noise ratio over which articulation scores vary from 0% to 100%, the articulation score, $A(g,y)$, will be equal to

$$A(g,y) = 0 \qquad \text{for} \qquad g < y \tag{11}$$

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$$A(g, y) = \frac{100}{d}(g - y) \quad \text{for} \quad y < g < y + d$$

$$A(g, y) = 100 \qquad\qquad g > y \, . \tag{11}$$

This is illustrated in Fig. 12 which is an approximation to the experimental relationships shown earlier.

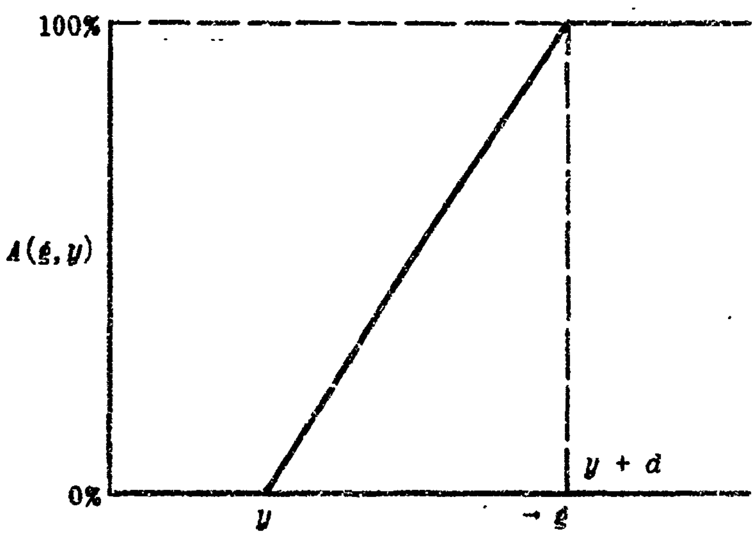

FIG. 12

ARTICULATION SCORE AS A FUNCTION OF ANTENNA GAIN

The reference level has been chosen so the level, y, corresponds to the threshold value of gain, i.e. y is the smallest value of the gain function for which finite articulation scores can be obtained. The parameter, y, is directly dependent on the noise level.

The transmission path may have any direction within the useful solid angle sector, Ω_s, that is, the sector about the aircraft covering all angles in azimuth and 60 degrees in elevation centered about the horizontal plane through the aircraft. The voice intelligibility index, $I(y)$, is now defined as the average of the function, $A(g, y)$, over the useful solid angle sector. In symbols

$$I(y) = \frac{1}{\Omega_s}\int_{\Omega_s} A(\xi, y)\, d\Omega \,, \tag{12}$$

where $A(\xi, y)$ is given by Eq. (11). Since the effective gain depends on the frequency, the index is also a function of the frequency of transmission.

The factor $I(y)$ is not a true average articulation score. In the actual system the parameter y is not a constant but a variable with time. The true value of this parameter fluctuates because of fading, and it also varies with the slower cyclic changes in ionospheric conditions. The term "voice intelligibility index" has been chosen to avoid confusion of this factor with actual articulation scores which do depend on these changes of the signal-to-noise ratio with time

The voice intelligibility index was calculated for a large number of different high frequency aircraft antennas designed for use on several different aircraft. A detailed discussion of this series of computations will be found in Appendix B. Figure 13 is typical of the results obtained. The voice intelligibility index is shown as a function of the inverse of the parameter y, so that the increasing coordinate corresponds to increases in the signal-to-noise ratio. Three antennas on a C-54 aircraft were considered; a fixed-wire antenna extending from an insulator at the top of the vertical fin to the forward end of the fuselage, an isolated section of the vertical stabilizer or tail-cap antenna, and an isolated section at the tip of a wing or wing-cap antenna. The position of these antennas on the aircraft are shown in Fig 14. Two results are apparent from the curves of Fig. 13. The voice intelligibility index is a linear function of the threshold level, in decibels, over a large range of this level. As shown in Appendix B, this behavior leads to a simple approximation to the voice intelligibility index. Of equal importance is the fact that these straight line portions of the voice intelligibility function for the different antennas are parallel to each other. The threshold level depends on the receiver; it is the same regardless of which particular aircraft antenna is used for transmitting. We can therefore compare the antenna systems at a fixed threshold level, and rate them by the difference in voice intelligibility index, using one of the antennas as a reference. Such a rating scheme is seen to be largely independent of the choice of threshold level at which the comparison is made.

A comparison of antennas directly in terms of voice intelligibility indices suffers the serious disadvantage that articulation scores are not directly related to the indices. The significance of such a measure in terms of system performance is therefore not well defined. In order to transform voice intelligibility indices into articulation scores, the variations with time of the threshold level would have to be known. The

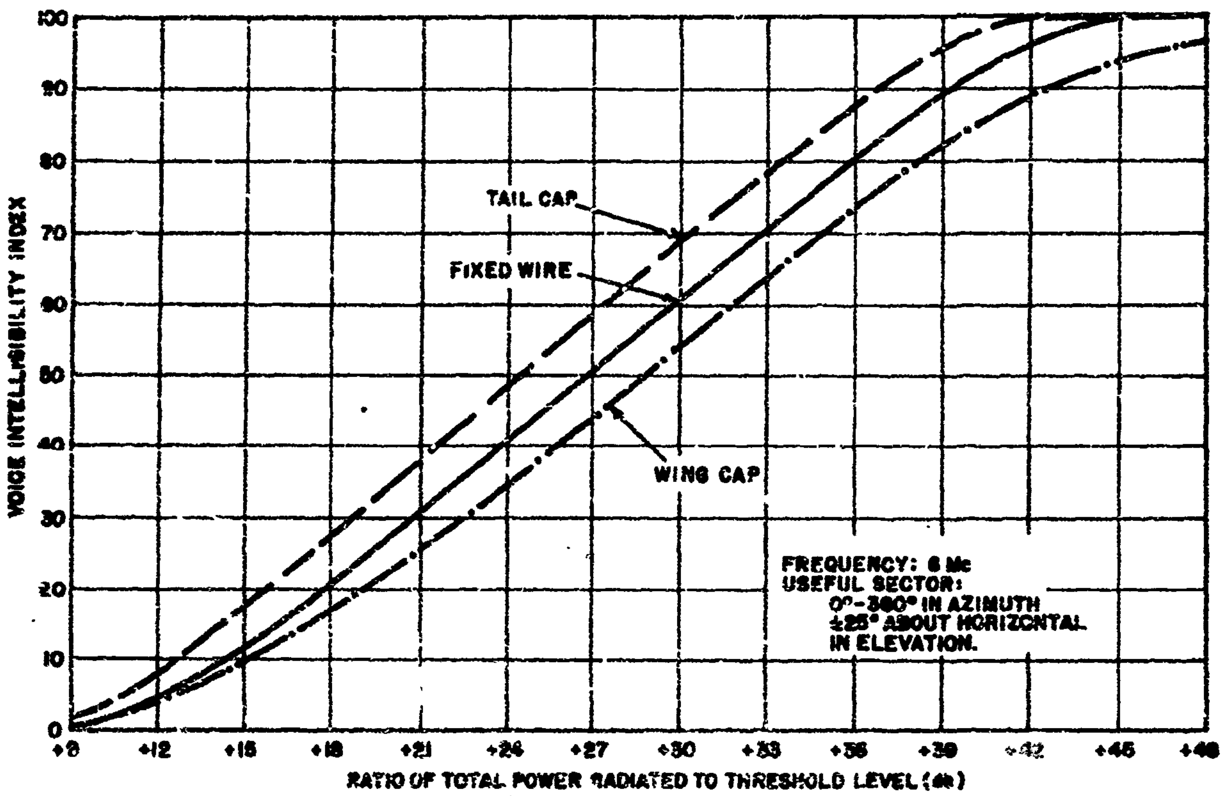

FIG. 13

VOICE INTELLIGIBILITY INDEX OF ANTENNAS ON C-54 AIRCRAFT, AS A FUNCTION OF THRESHOLD LEVEL

comparison of antenna systems can, however, be made in another fashion which avoids this difficulty. Let us assume that for a given threshold level two antenna systems have the same voice intelligibility index. The curves of Fig. 13 show that for this case, the indices would be very nearly the same for all threshold levels. Conversely, by increasing or decreasing the transmitted signal power radiated by the different antenna systems, the same voice intelligibility index can be obtained for all, and this change in power does not depend on the value of the index at which the comparison is made. Figure 15 illustrates this point. The increase

or decrease in radiated power shown here is that required to make the indices of the wing-cap and tail-cap antennas equal to those of the fixed-wire antenna. These power changes are obtained from the curves of Fig. 13 since, as can be seen from Eqs. (8) and (10), the difference in threshold level between antennas at a fixed value of the index corresponds directly to the required changes in signal power. The abscissa for these curves is the voice intelligibility index, and the required power changes are seen to be constant for most values of the index If several antenna systems

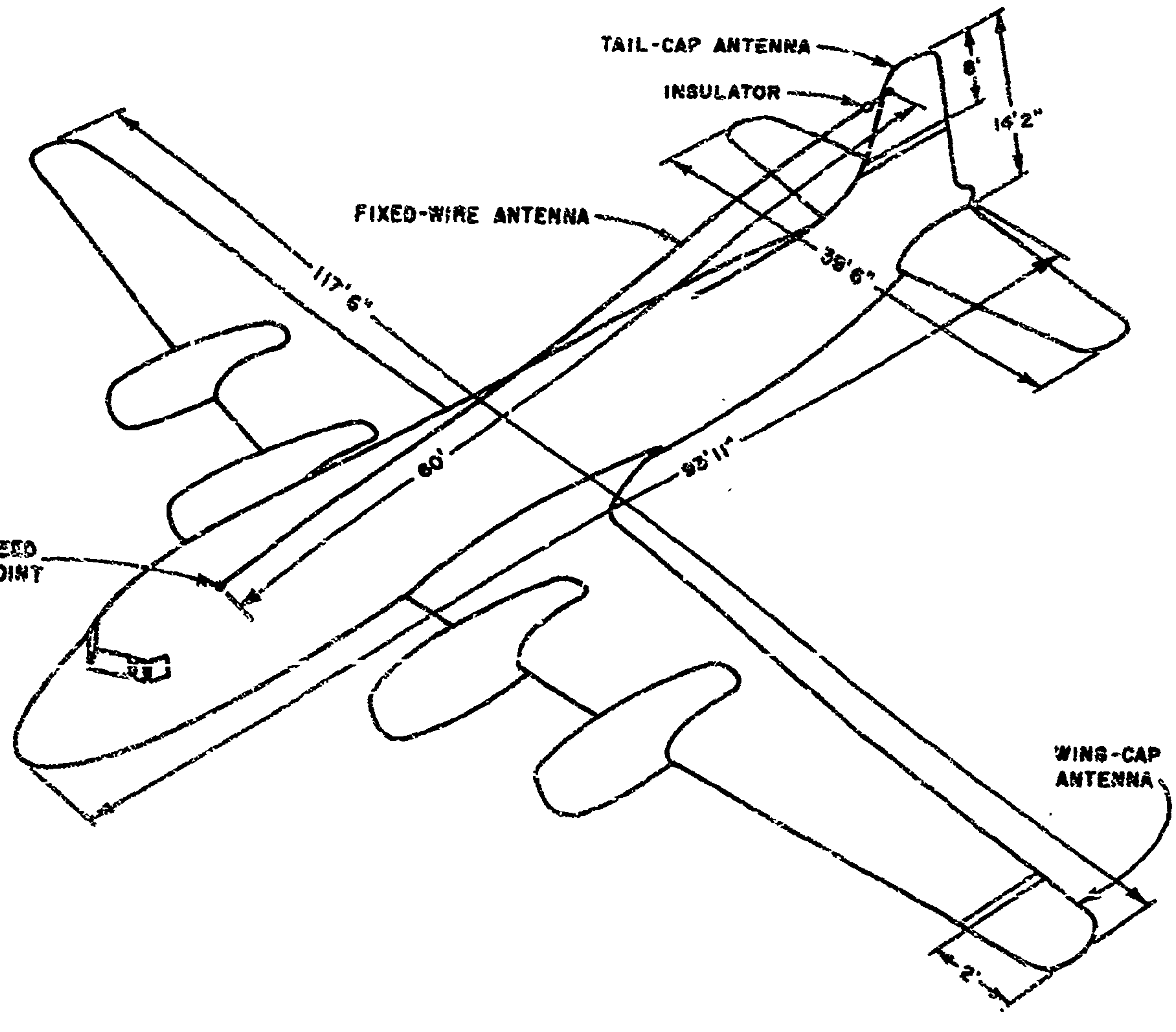

FIG. 14
H-F ANTENNAS ON C-54 AIRCRAFT

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have the same voice intelligibility index it can be shown that the average articulation scores observed over the systems would also be identical, independent of the ever present time variations in signal-to-noise ratio. The changes in signal power required to make the voice intelligibility indices of the antennas equal to those of the reference antenna therefore

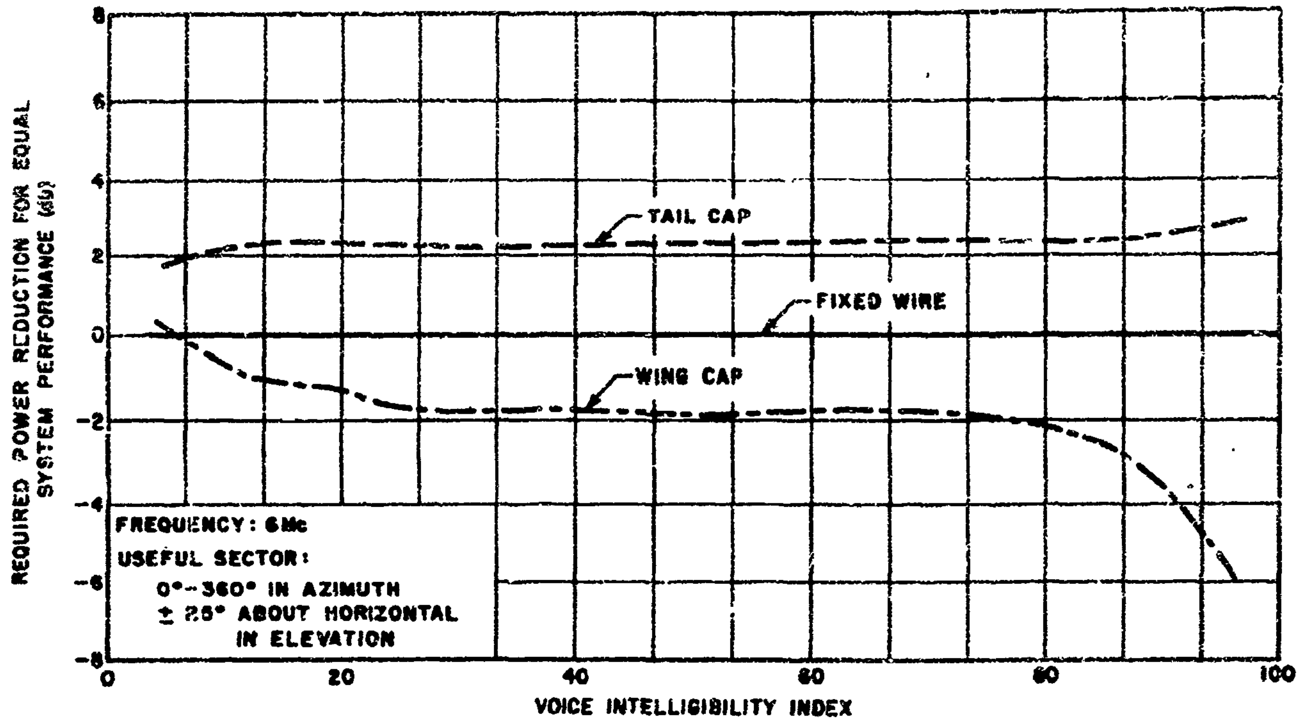

FIG. 15

COMPARISON OF FLUSH-MOUNTED ANTENNAS WITH A FIXED-WIRE ANTENNA ON C-54 AIRCRAFT. AS A FUNCTION OF VOICE INTELLIGIBILITY INDEX

provide a suitable measure of antenna performance. Such a measure can be visualized in terms of increases or decreases in the size, weight, and cost of airborne equipment resulting directly from the design of the h-f antenna. Furthermore, it is based on a significant parameter of the system as a whole since equal system performance here means equal average articulation scores; synonymously, if the system performance as defined here is the same, the same amount of intelligence can be transmitted over all these systems when a sufficiently long interval of time is considered.

The power changes required for equal system performance can be determined at other frequencies in the manner just outlined. In Fig. 16, the antenna ratings relative to those of the fixed-wire antenna are plotted as

a function of frequency. These curves are again representative of the results obtained for all the other antennas examined, as discussed in Appendix B. The greatest difference between antenna systems for the case illustrated is 6 db. This is the difference in performance between the tail-cap antenna and the wing-cap antenna on the C-54 aircraft at a frequency of 14 Mc. In other words, to obtain the same average intelligibility when using a wing-cap antenna, as that obtained when a tail-cap

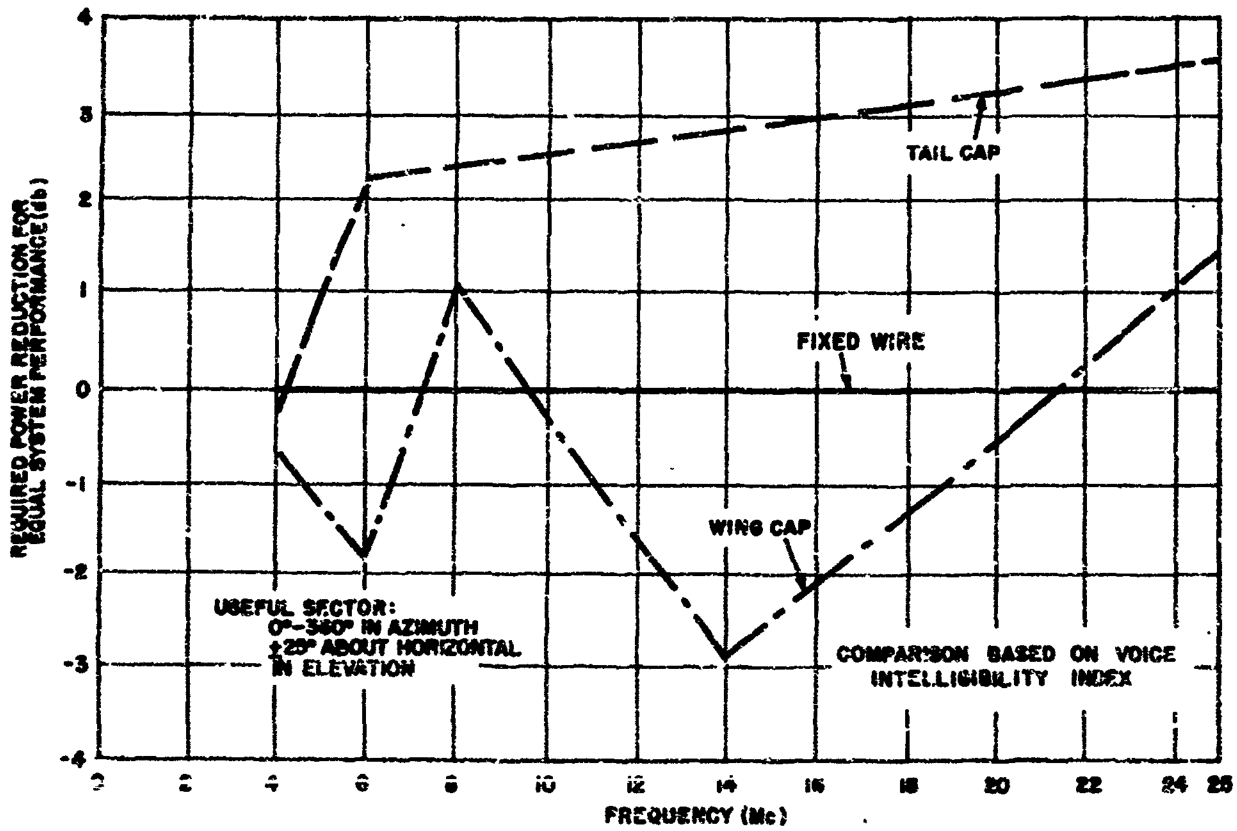

FIG. 16

PERFORMANCE OF ANTENNAS ON C-54 AIRCRAFT

antenna is used, the output power of the transmitter must be raised 6 db when transmitting over the wing-cap antenna. Now it should be remembered that the minute-to-minute variations of the signal-to-noise ratio due to fading are of the order of 20 db, and the changes in noise level and signal strength with ionospheric changes of longer period may be even greater The difference between antenna systems, while not unimportant, is small in comparison. In particular, any steps taken to make better use of the ionosphere, such as the careful selection of the frequency of transmission,

can bring about improvements in system performance which far exceed those obtainable by the use of a better antenna. As another example, operating procedures which do not strictly adhere to transmissions of standard words and phrases may nullify the system gain achieved by careful antenna design.

D. THE RADIATION PATTERN DISTRIBUTION FUNCTION

Assume an arbitrary but fixed noise level. It is now postulated that the system is useless when the signal-to-noise ratio is smaller than unity, and perfect when the signal-to-noise ratio exceeds unity. This does not correspond to the behavior of the system under discussion. Articulation scores may be thought of as approaching this function of the signal-to-noise ratio, with decreasing size of vocabulary. This was illustrated in Fig. 9 where, however, the articulation score was still far from behaving as a step function of the signal-to-noise ratio, even for a two-word vocabulary.

On the other hand, assuming this on off type of system behavior, a simple means of rating antenna systems is obtained, namely the radiation pattern distribution function. It is given by the fraction of the useful solid angle about the aircraft antenna, or about the equivalent antenna on the ground, over which the gain exceeds some arbitrary fixed minimum useful level. If $\mathscr{g}(\Omega)$ is again the effective gain function in decibels defined in Eq. (8), and y is the minimum useful level in the same units, the radiation pattern distribution function, $\mathscr{D}(\mathscr{g} > y)$, is found to be:

$$\mathscr{D}(\mathscr{g} > y) = \frac{1}{\Omega_u} \int_{\Omega_u} u(\mathscr{g} - y)\, d\Omega . \tag{13}$$

Here $u(\mathscr{g} - y)$ is the unit step function, that is

$$\begin{aligned} u(\mathscr{g} - y) &= 0 \qquad \mathscr{g} < y \\ u(\mathscr{g} - y) &= 1 \qquad \mathscr{g} > y \end{aligned} \tag{14}$$

Ω_u again stands for the useful solid angle sector about the antenna. The minimum useful level, y, is a parameter similar to the threshold level for the voice intelligibility index.

The radiation pattern distribution functions for the same three antennas on a C-54 aircraft are shown in Fig. 17. It will be noted that the change from the 100% value of the function to a value of 0% is accomplished in a very much smaller range of the parameter than a similar change in voice intelligibility index. Ratings based on the power change required for equal system performance are shown in Fig. 18. It should be

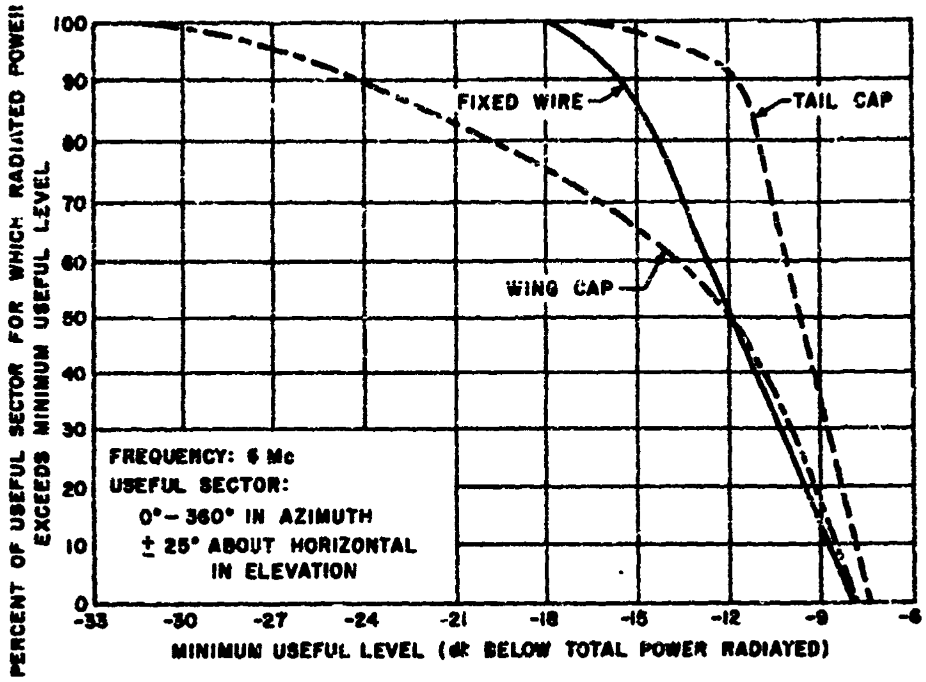

FIG. 17

RADIATION PATTERN DISTRIBUTION FUNCTION OF ANTENNAS ON C-54 AIRCRAFT

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understood that the meaning of the term "equal system performance" refers here to equal values of the radiation pattern distribution functions. This has no immediately apparent significance as far as the usefulness of the system as a whole is concerned. More serious is the fact that the power changes required depend very markedly on the value of the distribution function at which the comparison of antennas is to be made. For this reason the radiation pattern distribution function is not a convenient measure of the performance of high-frequency aircraft antenna systems.

The relation between voice intelligibility index and the radiation pattern distribution function should be cited. If d is again the marginal range of signal-to-noise ratios indicated in Fig. 12, the voice

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intelligibility index can be shown to be given by.

$$I(y) = \frac{100}{d} \int_{y}^{y+d} \bar{D}(g > u)\, du \; . \tag{15}$$

The voice intelligibility is a simple average over the distribution function, which accounts for the smoother behavior of the index, as compared to that of the distribution function.

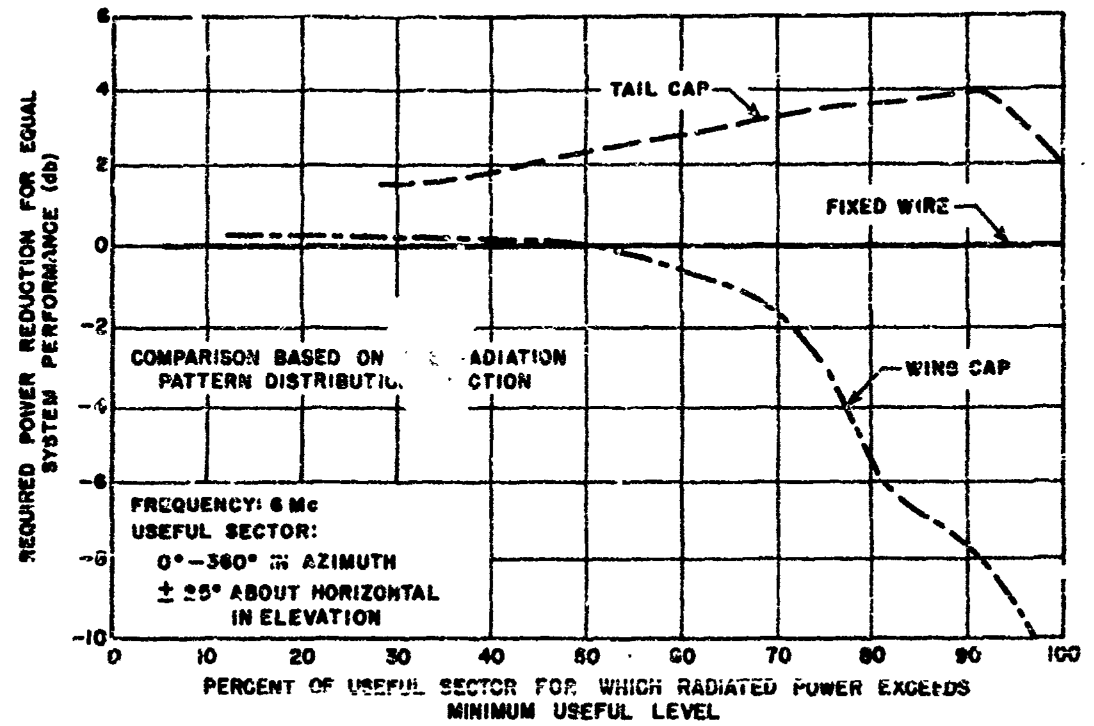

FIG. 18

COMPARISON OF FLUSH-MOUNTED ANTENNAS WITH A FIXED-WIRE ANTENNA ON C-54 AIRCRAFT

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E. THE ANTENNA SYSTEM EFFICIENCY

The antenna system efficiency is defined as the ratio of the power radiated into the useful solid angle sector about the antenna, to the total power available at the transmitter. If η_{tr} is the power transfer efficiency defined in Eq. (2) and $G(\Omega)$ is the gain of the aircraft antenna given by Eq. (6), the antenna system efficiency, η_s, is given by the integral

$$\eta_s = \frac{\eta_{t,r}}{4\pi} \int_{\Omega_u} G(\Omega)\,d\Omega \tag{16}$$

This can be considered as the product of the power transfer efficiency and of a radiation pattern efficiency, η_p, given by:

$$\eta_p = \frac{1}{4\pi} \int_{\Omega_u} G(\Omega)\,d\Omega \,. \tag{17}$$

The radiation pattern efficiencies of the tail-cap antenna, the wing-cap antenna, and the fixed-wire antenna of the C-54 aircraft are shown in Fig. 19. A point of interest is the small difference between the efficiencies of the different antennas at frequencies below 4 Mc. At these low frequencies, all antennas are equivalent to differently oriented

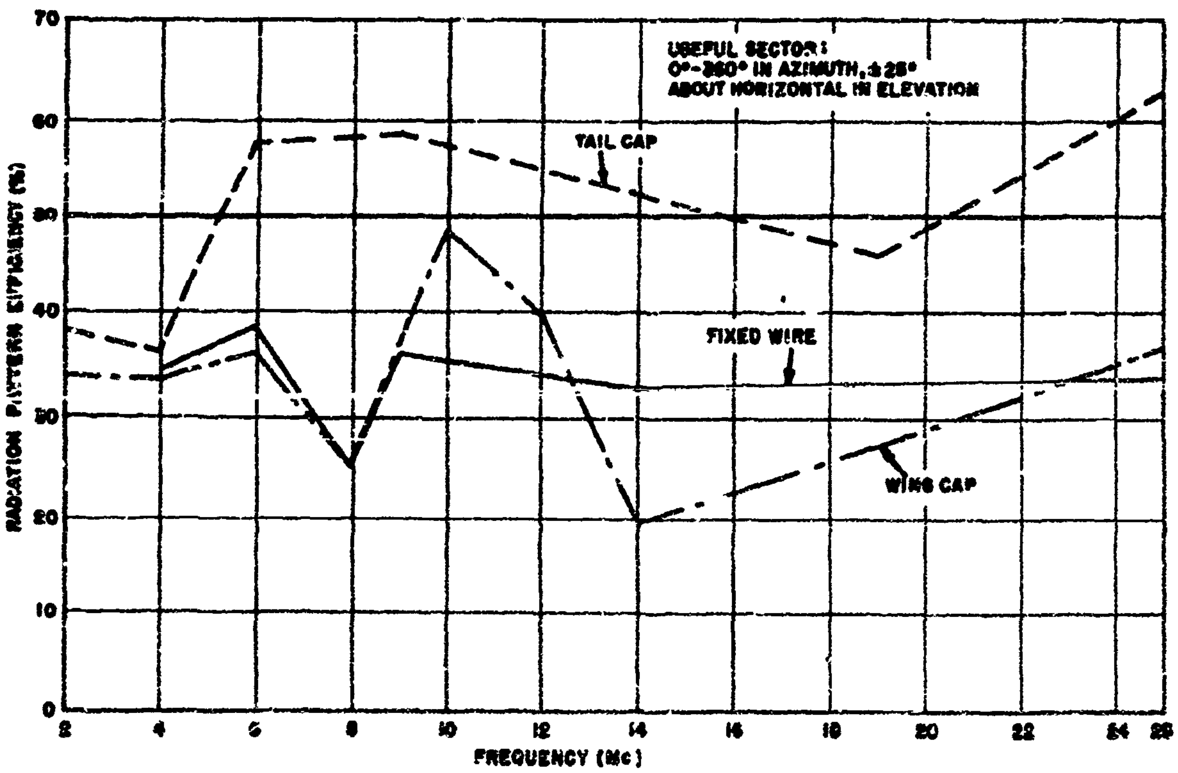

FIG. 19

RADIATION PATTERN EFFICIENCY OF H-F ANTENNAS ON C-54 AIRCRAFT, AS A FUNCTION OF FREQUENCY

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dipoles. Since the useful solid angle sector includes 50% of the area of a sphere about the aircraft, the differences in orientation of the axes of these equivalent dipoles do not lead to important differences in pattern efficiency. This behavior of the radiation patterns at the low end of the frequency band will allow the establishment of simplified performance standards at that end of the band A discussion of this is given in the following chapter.

The radiation pattern efficiency measures, in a simple fashion, the value of the radiation patterns of the system which makes use of the antennas. The radiation pattern efficiency is directly proportional to the gain function and can be calculated quite simply from the areas of the polar field plots usually obtained in measurements on aircraft models. Any losses in the system are accounted for by simple multiplication of the radiation pattern efficiency by the power transfer efficiency. The other methods for antenna evaluation which were just discussed are based on discontinuous functions of the antenna system efficiency and are therefore much more difficult to evaluate in practice. Furthermore, they all involve an additional parameter corresponding to the noise level and must therefore first be obtained as a function of this parameter before a meaningful comparison of the antenna systems can be made. The antenna system efficiency, on the other hand, is independent of the noise level.

The antenna system efficiency is the most convenient practical evaluation measure if its meaning can be interpreted in terms of the overall performance of the communication circuit. Fortunately there exists a simple relation between voice intelligibility indices and the antenna system efficiency, which was found to be satisfied to a good degree of approximation for all the antennas examined in Appendix B. This relationship is as follows

$$I(y) \simeq \frac{100}{d} [10 \log_{10} \eta_s - (y + C)] , \qquad (18)$$

where C is a constant depending on the reference level.

When using the voice intelligibility index, antennas were compared on the basis of equal system performance relative to a standard antenna. If the antenna system efficiency of the reference antenna is η_{s_r}, the amount by which the power transmitted over another antenna of system efficiency,

η_s, must be reduced to achieve equal average articulation scores, is found from Eq. (18) to be:

$$10 \log_{10} \frac{\eta_s}{\eta_{s_r}} \ (db) \ . \tag{19}$$

That is, the antenna system efficiency expressed in decibels relative to the efficiency of the reference antenna, gives directly the power change required for the average articulation scores observed over the antenna under consideration, to be the same as those observed for the reference system. To the degree to which the approximate expression of Eq. (18) holds, the antenna system efficiency is equivalent to the voice intelligibility index. Figure 20 illustrates this equivalence. The curves are a

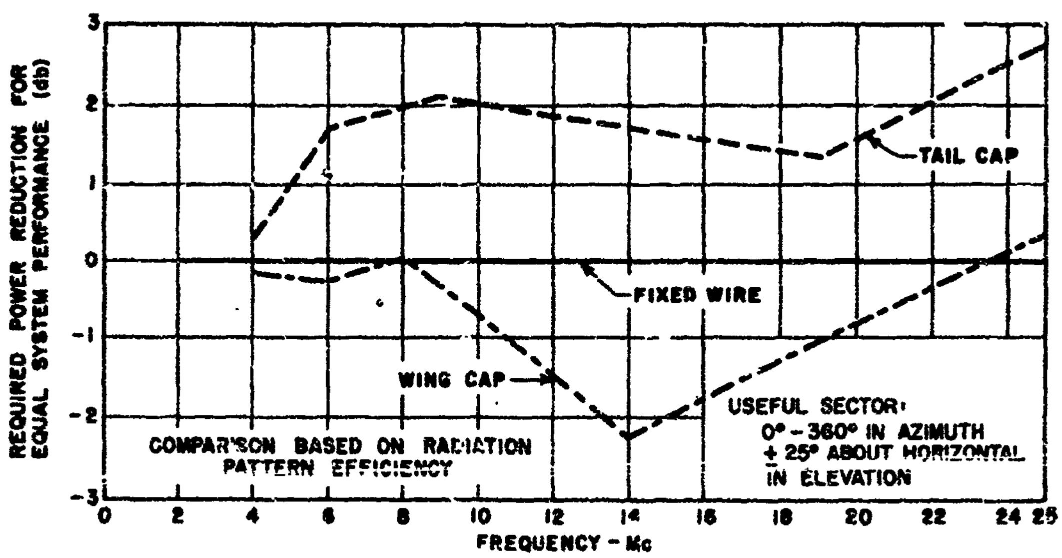

FIG. 20

COMPARISON OF ANTENNAS ON C-54 AIRCRAFT

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plot of Eq. (19) as a function of frequency, using the fixed-wire antenna as a reference. A comparison with Fig. 16 shows the close agreement between the evaluation based on the voice intelligibility index and the rating of antenna systems by means of the antenna system efficiency. Similar results were obtained for the other antenna systems examined in Appendix B.

It has thus been shown that the power changes required for equal average articulation scores can be determined directly from the antenna system efficiency. Antenna system efficiency has, then, exactly the same meaning as a system parameter, as the voice intelligibility index. The antenna system efficiency is therefore a suitable measure for the evaluation of h-f antennas, both insofar as its significance to the communication system is concerned, and as a practical quantity easily calculable from model and mockup measurements.

CHAPTER 6

PERFORMANCE STANDARDS

It has been shown that the antenna system efficiency can be used as a measure of aircraft antenna performance, equivalent in practice to ratings based on articulation scores. Articulation scores, however, like most subjective judgments of quality, serve only as a means of comparing different systems. In order to make use of a rating scheme based on articulation scores, therefore, a standard of comparison must first be defined. For the purpose of a performance specification it is then necessary to determine what constitutes a satisfactory antenna in terms of the difference in performance between the system under test and the standard system.

The choice of a suitable reference antenna system is quite arbitrary. It is possible to use a lossless isotropic radiator, perfectly matched to the transmitter by means of lossless networks and transmission lines. Such a standard has the advantage that its antenna system efficiency can be easily calculated. On the other hand, a comparison of the performance of this hypothetical antenna system with that of actual antenna systems is meaningless, unless the quality of performance under normal operating conditions of at least one of these antennas is already known. This procedure leads to a calibration of the arbitrary standard in terms of the performance of the system of known quality of performance. The meaning of the ratings of the remaining antenna systems, in terms of the reference, then has a definite operational significance.

Aircraft which utilize the h-f liaison system differ greatly in size and in configuration. It is therefore unreasonable to expect the same quality of performance of the h-f antennas on all aircraft. Under these circumstances the use of a single arbitrary standard system is a needless complication. Instead, a reference antenna can be defined for each type of aircraft; this antenna must have a physically possible configuration, the operational performance of which should be known as far as possible. The fixed-wire antenna is recommended for this purpose. It consists of a wire extending from an insulator at the top of the vertical stabilizer,

to the forward end of the fuselage. This type of antenna is the one most widely used at the present time and its performance from an electrical point of view has generally proven to be satisfactory. Since the length of the wire depends on the length of the fuselage this standard automatically adjusts itself to the size of the airframe for which an antenna is to be designed, and so takes into consideration the unavoidable changes in system performance caused by differences in size of various aircraft.

This discussion and the result of the previous chapter lead to the following scheme for the establishment of practical performance standards.

The measure of antenna performance for the purposes of the specification is the antenna system efficiency. The required magnitude of this efficiency is obtained from the ratio of the system efficiency of the antenna under test to that of a reference fixed-wire antenna. The performance of the reference antenna is assumed to be satisfactory regardless of the actual size and shape of the aircraft on which it is mounted.

The rating of antenna performance carried out in this manner will be different for different frequencies of transmission. The comparison of the proposed antenna and the standard antenna is therefore based on the *average* of the antenna system efficiencies. This average extends over all frequencies between 6 Mc and 24 Mc. The upper limit of this range is set by the equipment which, in turn, represents the upper limit of the frequencies which are generally useful for long distance transmissions over most parts of the sunspot cycle. The lower limit was chosen for two reasons. First of all, frequencies below 6 Mc are not often used for long distance transmissions and are therefore of lesser interest to the system as a whole. The second more important reason is the change in significance of the various factors contributing to the antenna system efficiency in the neighborhood of this frequency. Separate requirements are therefore placed on the performance of the system between 2 Mc and 6 Mc. These will be discussed presently. Since the fixed-wire antenna is assumed to provide satisfactory service, the specification requires that the average antenna system efficiency of the proposed antenna be equal to or exceed that of the standard antenna. Let it be repeated that equal performance in this sense means that the articulation scores observed over the systems under comparison are equal, on the average. Very little is gained, however, if the antenna system efficiency of the antenna under test greatly exceeds that of the reference antenna at any one frequency, while a rating far below that of the reference seriously impairs the performance near such a

frequency. It is therefore required, in addition, that the antenna system efficiency of the proposed antenna never be less than 50% below that of the reference antenna. In terms of articulation score this is roughly equivalent to tolerating a loss of about ten percentage points below the average articulation score observed over the fixed-wire antenna at any one frequency. Such losses must be compensated for by gains at other frequencies, since the performances of the antenna and reference antenna are to be the same when averaged over all frequencies.

It should now be recalled that the antenna system efficiency is essentially a product of two factors -- the radiation pattern efficiency and the power transfer efficiency between the transmitter and space. At frequencies above about 6 Mc almost any antenna system of reasonable design will provide a high power transfer efficiency and for this end of the band, the choice of an adequate antenna is based largely on the radiation patterns. At the low end of the band, however, the radiation pattern efficiencies of all antennas were found to be almost identical, while efficient impedance matching is difficult, and losses in the antenna proper represent an appreciable fraction of the power delivered to the antenna terminals. The performance of the antenna system at frequencies between 2 and 6 Mc can therefore be based on the power transfer efficiency alone. The impedance function of the fixed-wire reference antennas is such that high power losses in physically realizable matching circuits between the transmitter and the antenna are unavoidable. The power losses in the antenna itself are probably at least as large as the matching circuit losses at the low frequencies. Such losses are difficult to estimate from measurements on models of the aircraft. Consequently, for the low end of the band, the fixed-wire antenna is not a suitable and practical reference on which to base the performance of the antennas. On the other hand, the losses in antennas involving isolated sections of the airframe can usually be predicted with considerable accuracy from simple measurements on mocked-up sections of the antenna gap region. In addition, such antennas involving more massive structures can be matched to the transmission line more efficiently than the fixed-wire antenna. The specification therefore establishes an absolute standard of power transfer efficiency at not less than 25% for any frequency between 2 Mc and 6 Mc and not less than 50% for the average of the efficiencies over this frequency range. These requirements are, of course, somewhat arbitrary; however, they represent values which can reasonably be expected in practice, and at the same time eliminate antenna designs which are obviously inefficient, yet have sometimes

been suggested in the past. The size of the airframe still influences the performance of h-f antenna systems. The requirements on the power transfer efficiency are accordingly waived for frequencies below which the dimensions of a given path length on the airframe is smaller than a stated fraction of the wavelength. The critical path chosen is the one leading to the first resonance of the impedance function of tail-cap antennas as discussed in connection with Fig. 7.

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CHAPTER 7

FLIGHT TEST EVALUATION OF AIRCRAFT ANTENNAS

A. INTRODUCTION

The majority of arguments which lead to the choice of the antenna system efficiency as a measure of high-frequency aircraft antenna performance are based on data obtained from measurements made on aircraft models and on theoretical deductions derived from such data. This choice must be confirmed by tests on actual antennas mounted on actual aircraft, operating under the usual conditions for high-frequency transmissions. An aircraft ideally suited for this type of test was made available to Stanford Research Institute by the Air Force. This aircraft, a C-54 transport, has two flush-mounted high-frequency antennas, a wing-cap antenna, and a tail-cap antenna; a fixed-wire antenna can also be installed. A direct comparison of the performance of the cap-type antennas with that of the reference fixed-wire antenna system can therefore be made by tests on a single aircraft.

The antenna systems are to be compared on the basis of average articulation scores. In order to obtain an average, scores must be measured for transmissions over many different distances, for all possible azimuth angles of the transmission path with respect to the aircraft, and for a large number of different ionospheric conditions. These observations must be made simultaneously on all three antenna systems since ionospheric conditions are not stable enough to allow a comparison to be made of tests performed over different time intervals. In addition, tests should be made at different frequencies of transmission within the range of interest. In practice, it is not possible to undertake such an exhaustive series of tests Ionospheric conditions vary not only with the time of day, but also with the seasons and with the sun spot cycle, and with different geographical locations of the transmission path. However, as shown in Appendix C, the comparison of antenna systems is almost independent of such changes in ionospheric conditions, except insofar as they affect the best frequency for transmission. Tests over different distances of transmission ranging from about 1000 miles to 3000 miles are expensive and time

consuming. Many of the tests were therefore performed over a single path, with transmissions originating at Dayton, Ohio and with the aircraft flying in the vicinity of San Francisco, California. The extent of the vertical sector over which the signal arrived at the aircraft was consequently considerably smaller than that considered to be useful to the system in general. Tests were, however, performed over a large sample of azimuthal directions of the transmission path with respect to the aircraft, and for a series of different frequencies of transmission.

The necessity of simultaneous articulation testing over the three antennas on the aircraft also causes considerable difficulty. An indirect method of testing was devised, involving the measurement of signal-to-noise ratio distributions from which average articulation scores could be computed. The validity of this method was established in a series of preliminary experiments over a fixed ground-to-ground link.

In general, transmission tests involving aircraft in flight are not only exceedingly expensive, but the results are usually of poor accuracy. A large number of both physical and subjective variables is always involved, many of which cannot [illegible]ictly controlled. The results of a small number of tests are often [illegible]tely scattered. Accordingly, a large number of tests are required to [illegible]tain accurate estimates of the mean which, in turn, involves prohibitive costs. In the evaluation of high-frequency aircraft antennas wherein the differences between the antennas are expected to be small, the scattering of flight test results may obscure the effects predicted from theory. The tests, nevertheless, were useful since they confirmed the prediction that the differences between antennas are of the same order of magnitude as those predicted from theoretical considerations. The fact that scattering of the data obtained during flight tests partially obscures the predicted variations in performance is equivalent to the lack of importance of such variations in the actual operational use of the system. Detailed descriptions of the method of testing and of the actual flights performed will be found in Appendices E, F, and G.

Other, simpler methods for the flight test evaluation of high-frequency aircraft antenna systems were investigated. They consisted of two separate tests corresponding to the requirements on the system in the frequency range from 2 Mc to 6 Mc and those for the range from 6 Mc to 24 Mc. The first of these, described in Appendix H, gives a direct measurement of the power transfer efficiency of the antenna systems. The

second series of measurements, leading directly to an estimate of the antenna system efficiency, utilized back scattering of the sky wave at points of ground reflection. A description of this technique will be found in Appendix I The necessary apparatus for these two methods of experimental evaluation of actual antenna systems has been developed sufficiently to demonstrate the feasibility of these measurements.

The series of flight tests confirmed the results derived from the theoretical and empirical considerations. It is therefore unnecessary to perform similar tests as part of the development of antennas for other aircraft. This is one of the most important conclusions of this investigation. Once a flush-mounted h-f antenna has been installed on an aircraft, no major alterations can be made in its design even if subsequent flight tests should show it to be unsatisfactory. The tests conducted here demonstrate that an antenna design arrived at by the methods described will actually perform in the manner predicted from the model data.

B. INDIRECT MEASUREMENT OF AVERAGE ARTICULATION SCORES

The simultaneous measurement of articulation scores, using three different antenna systems on one aircraft, is a difficult task. Articulation scores must be based on the reception of an entire word list. These word lists are specially constructed to obtain phonetic balance, and are carefully graded as to the difficulty of identifying the words. Scores based on transmissions of parts of such lists will lead to meaningless results. The time required for the transmission of a list is about four minutes; consecutive use of the different antennas is therefore precluded because of ionospheric variations during time intervals of this magnitude. On the other hand, coupling between antennas at some frequencies may alter the characteristics of the antenna systems sufficiently to invalidate the results obtained from simultaneous tests using several antennas on the same aircraft.

In order to overcome these difficulties, an indirect method for obtaining articulation scores was devised. This method is based on the relationship which is found to exist between the signal-to-noise ratio at the receiver output, and articulation scores. Knowing this relationship and the statistical distribution of the signal-to-noise ratio measured for a given time interval, it is possible to compute the average articulation scores which would have been observed for this same period.

Two quantities are required in order to compute average articulation scores: the relationship between signal-to-noise ratios and articulation scores, and the distribution of the signal-to-noise ratio. The dependence of articulation scores on the signal-to-noise ratio was discussed earlier. The curve labeled "white noise," of Fig. 11, shows the relationship which was used for the tests discussed here.

The distribution of the signal-to-noise ratio is obtained by actual measurements on the aircraft. For a fixed location of the transmitter and the aircraft, a different distribution is obtained for each heading of the aircraft. Since all headings are considered as being equally useful, the function of interest is the average of all these distributions. Thus, let

$$\mathfrak{P}_\phi(u > z)$$

be the percent of time during which the signal-to-noise ratio, u, exceeds a level of y db while the aircraft heads into the direction, ϕ, with respect to the transmission path. The average distribution is then given by

$$\overline{\mathfrak{P}}(u > y) = \frac{1}{2\pi} \int_\phi \mathfrak{P}_\phi(u > y)\, dy \; , \qquad (20)$$

from which the average articulation score, $\overline{A}$, is obtained as

$$\overline{A} = \int_{-\infty}^{+\infty} \overline{\mathfrak{P}}(u > y) \, \frac{dA(y)}{dy} \, dy \; . \qquad (21)$$

$A(y)$ is the articulation score as a function of the signal-to-noise ratio, and the derivative of this function can be obtained from the curve shown in Fig. 11. The average articulation score is obtained over the same set of conditions as the average signal-to-noise ratio distribution.

The function $A(y)$ is found from articulation tests performed in the laboratory. The flight tests then involve only the measurement of signal-to-noise ratio distributions. To obtain these distributions, a carrier at the proper frequency for transmission is modulated with one or two audio tones of fixed frequency. These transmissions are recorded at the receiver, and later played back through an analyzer. In the analyzer, signal and noise are separated by means of narrow band filters, and

compared in a differential amplifier. Whenever the power in the signal circuit exceeds that in the noise circuit, a counter which counts at a constant rate is set in operation. The count is thus directly proportional to the fraction of time during which the signal exceeds the noise. A calibrated attenuator in the signal circuit makes it possible to measure the value of the distribution function at various desired levels.

It is not at all obvious that average articulation scores can be computed in this fashion for sky-wave signals. In fact it would appear that fading and other distortions produced by the ionosphere might deteriorate the intelligibility of the circuit to a much larger extent than that predicted from the signal-to-noise ratio distributions and Eq. (21). A series of tests was therefore undertaken to check the validity of the method. For this purpose, radio station AF5XE at Wright-Patterson Air Force Base, Dayton, Ohio alternately transmitted word lists and periods of carrier modulated by the fixed audio tones. The word lists used in these tests were the same as those used in establishing the relationship between articulation scores and signal-to-noise distributions. The audio tones were adjusted to the same power level as the average speech power of the word lists. These transmissions were received at Palo Alto, California and recorded on magnetic tape. The word lists were then played back to a group of listeners to obtain articulation scores. The audio tone periods were analyzed to obtain signal-to-noise ratio distributions from which average articulation scores were computed by means of Eq. (2).

Transmissions of word lists and audio tones were recorded at Palo Alto, over a period of about four months during summer and fall of 1952. About forty half-hour periods of recordings were analyzed. Each of these contained four word lists and four tone periods. For all these tests, the articulation scores obtained from the listeners, and those computed from the signal-to-noise ratio distributions agreed, on the average. The difference between computed and measured scores is normally distributed, indicating the absence of a systematic error. The standard deviation of the error is 12% in articulation score. This agreement is sufficiently close to permit the application of this indirect method of measuring average articulation scores to the case of sky-wave transmission where fading is a dominant factor.

C FLIGHT TEST PROCEDURE

The emphasis in the evaluation of antennas is to be based on the case when the aircraft is transmitting to a ground station. The flight tests, however, are more easily explained when reception takes place on the aircraft, and this case will be assumed here. The extension of the method to the evaluation of the antennas as transmitters of energy to space will be discussed at the end of this section.

One of the main advantages of the indirect method of measuring average articulation scores is the fact that a single receiver can be swtiched cyclically to the antennas under test, at a rate much faster than would be possible if entire word lists had to be received. This switching rate should be slow enough to obtain an adequate sample of the signal-to-noise ratio as received over each antenna, yet fast enough so that the changes of the statistics of the signal-to-noise ratio distribution remain small during a switching cycle. In testing the three antennas of the C-54 aircraft, the receiver was switched from one antenna to another about once every fifteen seconds.

The flight tests were conducted as follows. A distant station, usually AF5XE at Dayton, Ohio, transmitted the audio tone modulated carrier at the predicted frequency for optimum transmission over the path to the aircraft. The modulation level and the power level at the transmitter were kept constant during the entire test. The receiver on the aircraft was tuned to these transmissions and the audio output was recorded on magnetic tape while the input terminals of the receiver were switched from one antenna to another in the manner just described. Three audio tones at frequencies above the pass band of the receiver were recorded on the tape in synchronism with the antenna switching cycle. These tones identified the particular antenna used for reception at any given time. During these transmissions, the aircraft flew over a series of straight-line courses differing in heading by 15 degrees, staying on each heading for 2½ min. All required directions of arrival of the signal, with respect to the aircraft, were sampled by a series of 24 such straight-line courses. In order to minimize the effect of ionospheric variations during the time required to complete such a test, the actual course consisted of four interlaced hexagonal paths. The first sampling of directions took place every 60 degrees, and the succeeding hexagonal flight patterns provided the additional coverage of direction to give samples of the signal-to-noise ratio at 15 degree intervals. The recordings were analyzed to obtain signal-to-

noise ratio distributions from which average articulation scores could be computed by means of Eqs. (20) and (21).

The flight tests discussed so far, have been for the case in which the aircraft antennas are used for receiving. Of more interest for evaluation of the aircraft antennas, is the case of transmission from the aircraft to a ground based receiver. Let it be assumed at first that tests are carried out in the manner described for reception on the aircraft, with the difference that signal-to-noise ratios are recorded at a ground based receiver tuned to transmissions from the aircraft. An analysis of recordings of noise alone, for such a fixed ground station over a period of about one hour, shows that atmospheric noise is distributed with little deviation from its mean value. The deviation of the fading sky-wave signal, on the other hand, is many times larger. The signal-to-noise ratio as recorded on the ground, over a period of less than about one hour, has therefore essentially the distribution of the signal, and the noise can be considered as a constant. To test the aircraft antenna for the transmitting case, therefore, one can still use reception on the aircraft of transmission sent out by the ground station, as long as the audio signal power output of the receiver is proportional to the power of the fading sky-wave signal. This is the case if the automatic volume control of the receiver is made inoperative. The noise recorded on the aircraft is ignored and the fixed noise which would have been received on the ground is introduced artificially when analyzing the variations of the signal. It is, of course, necessary to operate within the linear region of the receiver. The signal is kept within this range by means of a calibrated attenuator which takes the place of the usual radio frequency volume control.

D. FLIGHT TEST RESULTS

The performance of a tail-cap antenna, a wing-cap antenna, and a fixed-wire antenna on the C-54 aircraft was measured in the manner just described. Figure 21 is a photograph of the aircraft, which shows these antennas. Most of the transmissions originated at Dayton, Ohio, while the aircraft flew over the hexagonal test patterns in the vicinity of Palo Alto, California; Las Vegas, Nevada; and San Antonio, Texas. For the San Antonio flight, Palo Alto also served as a transmitting station. These locations were chosen in order to test the antennas over the desired frequency range and yet be able to utilize the optimum frequency of

FIG. 21

C-54 AIRCRAFT FOR TESTING LIAISON ANTENNAS

transmission for each of the tests. For the same reason, flights took place during both day and night.

A typical example of signal power distributions in shown in Fig. 22. These curves give the percent of time during which the signal received over each of the antennas, exceeds the indicated level. The different

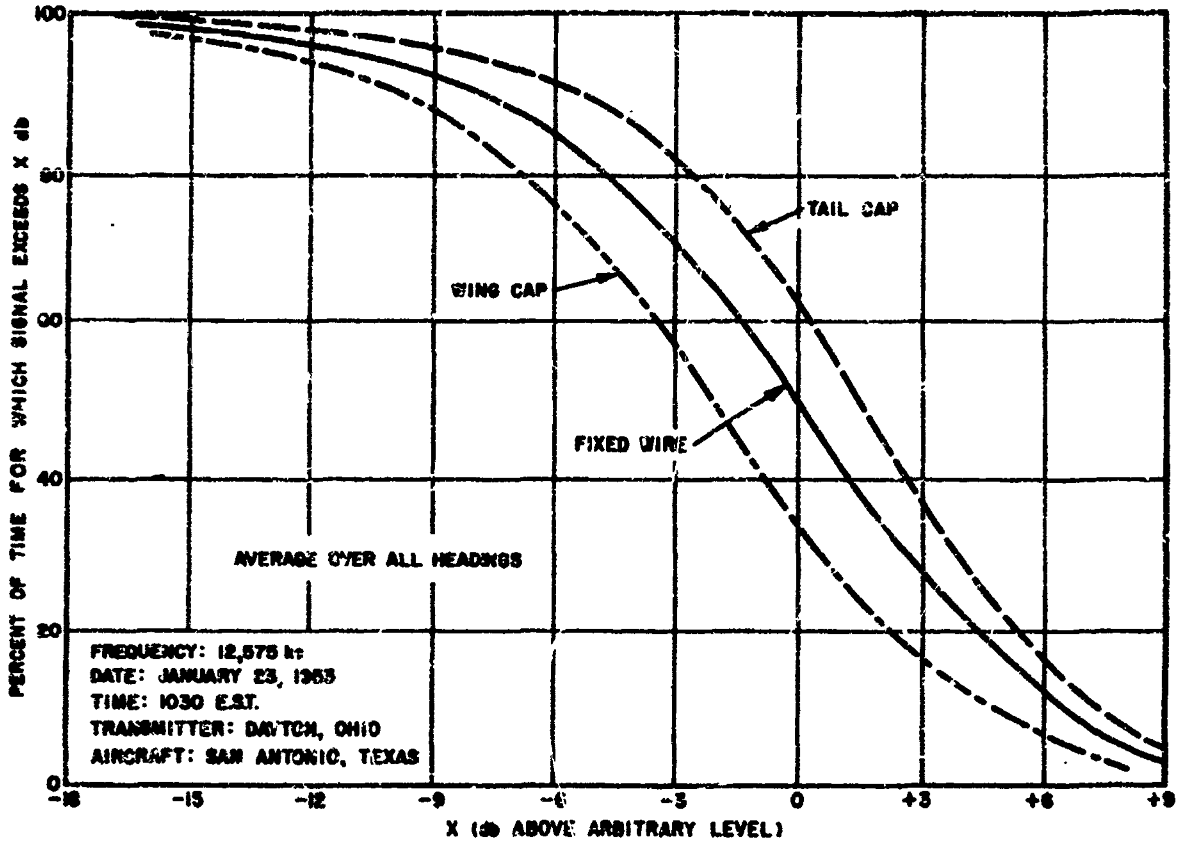

FIG. 22
DISTRIBUTION OF SIGNAL POWER RECEIVED ON AIRCRAFT

A-6060-F-292

signal levels making up these distributions are due both to fading and to changes in gain of the antennas as the aircraft flies on the various headings making up the complete flight pattern. The distributions correspond to those given by Eq. (20). From these curves, average articulation scores can be computed by means of Eq. (21). Another advantage of this method of arriving at articulation scores now becomes apparent. Fixed changes in transmitted power or similar changes in noise levels are simply equivalent to a shift of the reference level for the abscissa of Fig. 22; neither the shape nor the relative position of the curves is affected by

such changes. A single measurement of the kind illustrated can therefore be used to calculate average articulation scores for any desired median value of the signal-to-noise ratio. A separate measurement would have been required for each of these cases had articulation scores been measured directly.

Figure 23 is a plot of the average articulation scores which would be observed when transmitting over the three antennas on the C-54 aircraft, over a path for which the optimum frequency is in the neighborhood of 12.5 Mc. The scores are given as a function of the median signal-to-noise ratio

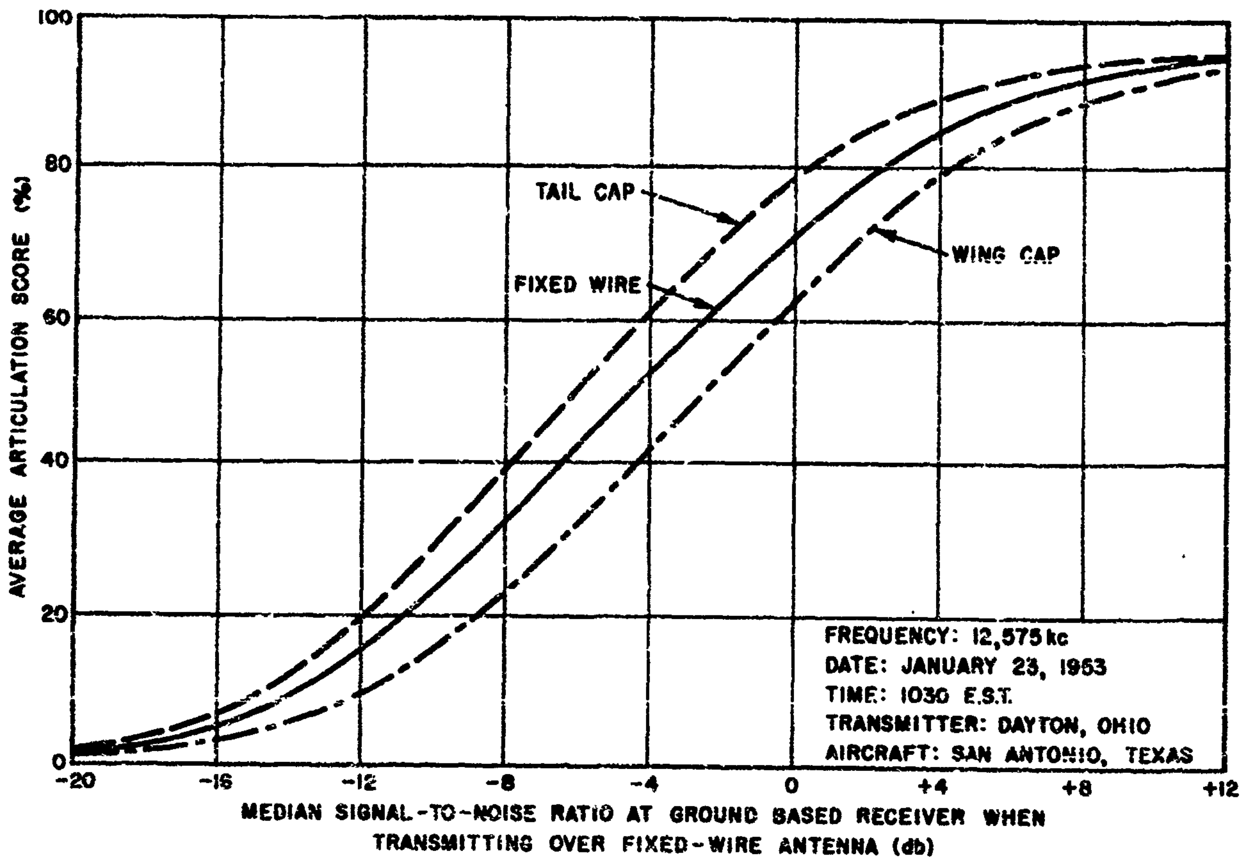

FIG. 23

FLIGHT TEST EVALUATION OF ANTENNAS ON C-54 AIRCRAFT

A-60SC-F-253

observed at a receiver on the ground, when transmitting over the fixed-wire antenna. These curves should be compared with those showing the voice intelligibility index as a function of threshold level, such as shown in Fig. 13. These two sets of curves differ for two reasons. The

average articulation scores obtained on flight tests depend on the entire antenna system. They include the effects of ohmic losses in the various elements of the system, as well as losses caused by incomplete matching of the antennas to the transmission lines. Furthermore, the signal-to-noise ratio, as measured during flight tests, is subject to fading. The voice intelligibility index, on the other hand, was calculated from the radiation patterns alone, although corrections for the various losses could have been applied. These losses can be estimated from measurements on models, and methods for doing this are outlined in the specification. A detailed discussion of the way in which the power transfer efficiency can be found during the preliminary design of the antennas will be given in Part II of this report.

In the discussion of the voice intelligibility index, it was pointed out that the same overall performance of the three antenna systems at all threshold levels can be obtained by a single adjustment of the power radiated from the individual antennas. A similar result is evident from the experimental curves of Fig. 23. Here again, a fixed change in median signal power will make the average articulation scores observed over the tail-cap antenna, for instance, equal to those observed over the fixed-wire antenna for all median values of the signal-to-noise ratio. This power change can therefore be used to rate the performance of the cap-type antennas, relative to that of the fixed-wire antenna, and, as shown earlier, these ratings should correspond to those obtained on the basis of the antenna system efficiency.

In Fig. 24, the performance of the cap-type antennas is compared with that of the fixed-wire antenna, at all the frequencies at which measurements were made. At each frequency, these curves show the amount by which the power transmitted over the particular antenna should be reduced in order to obtain the same average articulation scores as would be observed when using the fixed-wire antenna. The difference in performance of the antennas at the low frequency end is governed almost entirely by the differences in ohmic power losses in the antenna matching network and in the antenna gap structure. This accounts for the better performance of the wing-cap antenna as compared to the tail-cap antenna. The Fiberglas laminate used to cover the isolating gap of the latter was found to be strongly hygroscopic. For instance, at 4.5 Mc. only 58% of the power entering the tail-cap antenna terminals was actually radiated; 42% was dissipated in the gap structure. The wing-cap antenna, on the other hand, radiates 92%

of the power incident on its terminals at this frequency. Above about 9 Mc, the tail-cap performs consistently better, and the performance of the wing-cap antenna is worse than that of the fixed-wire antenna. This is in agreement with the subjective judgment made by the crew which carried out these flight tests.

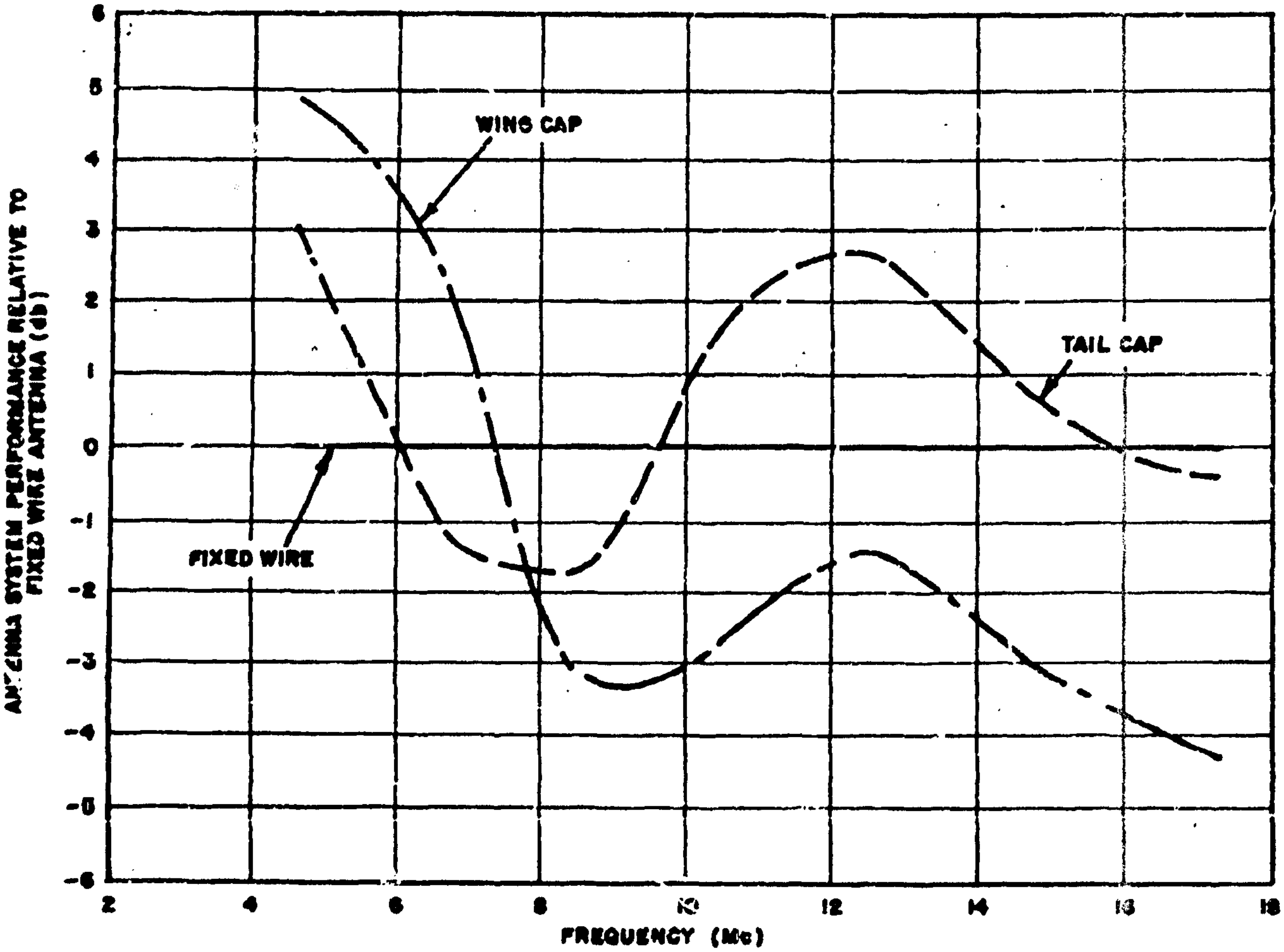

FIG. 24

FLIGHT TEST EVALUATION OF ANTENNAS ON C-54 AIRCRAFT

A-006C-F-254

In order to compare the flight test data with performance ratings based on measurements made on models, corrections must be made for the ohmic losses and mismatch losses of the actual antenna systems. The efficiency of power transfer between the transmitter output terminals and the antenna input terminals was therefore measured on the aircraft by the "Three Impedance Method." This method of measurement is described in

section 4.4.5.2.2 of the specification (Appendix A). The power losses in the wing-cap and tail-cap antennas themselves were estimated by comparing the antenna impedances measured on the aircraft in flight, with those obtained from measurements on models where the gap region is not filled with dielectric material. Estimates of the antenna efficiencies were, however, obtained only for frequencies below 6 Mc. Both of these antennas could then be compared on the assumption of 100% power transfer efficiency between the transmitter and space. Similar estimates were made of the losses in the fixed-wire antenna. These losses are high and therefore determine, to a large extent, the performance of the antenna at the low end of the frequency range. The measurements of the losses of the fixed-wire antenna were found to be of insufficient accuracy, so that the performance of this antenna could not be reduced to the case of 100% power transfer efficiency.

When all of the power fed into the transmission line at the transmitter is radiated into space, the only remaining antenna system parameter is the radiation pattern. In order to determine how well the performance of the actual antennas agrees with the data based on model measurements, the flight test results must then be compared with the radiation pattern efficiencies. Since it was not possible to determine the performance of the fixed-wire antenna when all losses are reduced to zero, the flight test and model data were compared by rating the tail-cap antenna relative to the performance of the wing-cap antenna. Figure 25 shows this comparison as a function of frequency. The maximum difference between the flight test results and those predicted from measurements on aircraft models is never more than 3 db and it is considerably less than that over most of the frequency range. Errors of this magnitude are not only well within the experimental error but, more important, they are relatively insignificant when compared to the large variations in signal strength to which the system is subjected by the ionosphere.

The flight tests have therefore demonstrated that an antenna design based on model measurements will perform essentially in the manner predicted. An antenna system satisfying the specification will indeed provide, on the average, the same intelligibility of speech transmitted over it as would be obtained with the fixed-wire antenna system so widely used today.

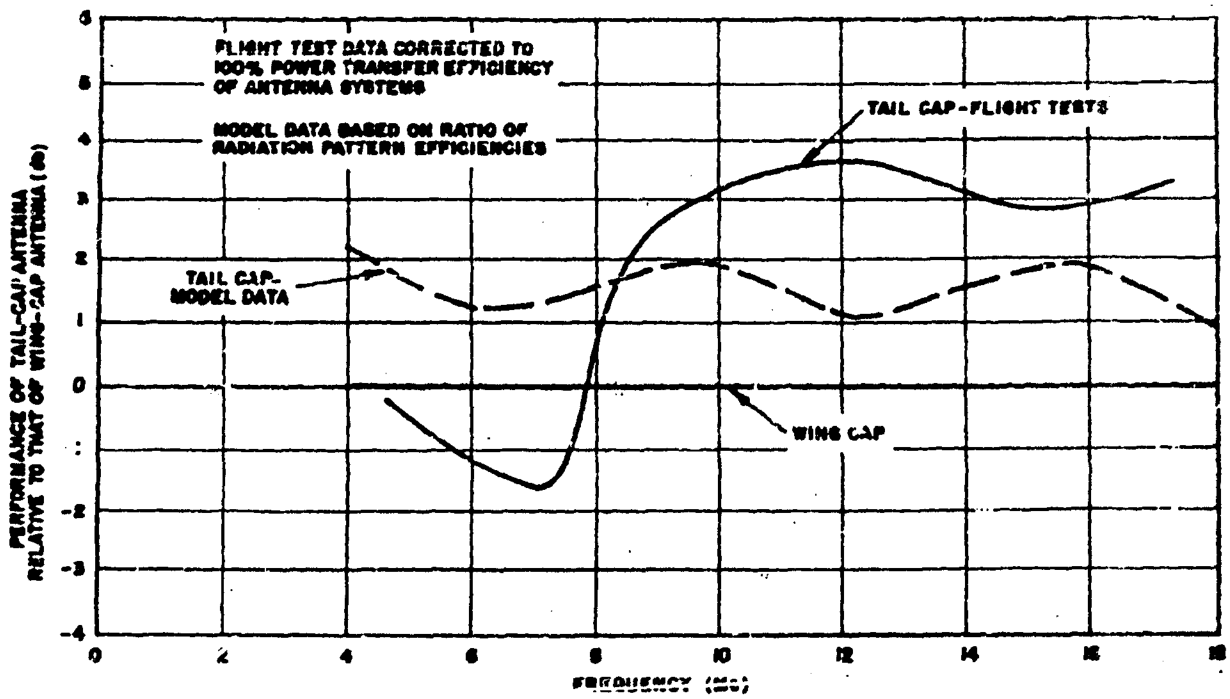

FIG. 25

COMPARISON OF PERFORMANCE EVALUATION BASED ON MODEL DATA, WITH THAT BASED ON FLIGHT TESTS

CHAPTER 8

SUMMARY AND CONCLUSIONS

Articulation scores have been chosen as the primary measure of the effectiveness of the high frequency air-to-ground and ground-to-air liaison system. The airborne antennas are then rated in accordance with the change they produce in the percentage of words correctly identified over the system. Such a measure is, of course, relative, and some reference antenna must be defined on the basis of which the comparison is to be made. Because of its satisfactory performance in the past, the fixed-wire antenna was chosen as the standard of comparison.

The antenna system efficiency is proposed as a practical measure of antenna performance. Data obtained solely from measurements on aircraft models and mocked-up portions of the airframe lead to these efficiencies by simple computations. Ratings based on the antenna system efficiency give essentially the same results as an evaluation in terms of articulation scores. The proposed method of measuring antenna performance therefore retains a definite meaning insofar as the operation of the system as a whole is concerned. At the same time, the method can be applied well in advance of construction of the actual antenna.

The results of a flight test program have shown that the antenna system efficiency is indeed a measure of average articulation scores. In these tests, three high-frequency antennas on a C-54 aircraft were compared under actual operating conditions. The comparison was made on the basis of average articulation scores, which were measured simultaneously using the three airborne antenna systems. A special indirect method of measurement was devised, which eliminated all actual articulation tests on the aircraft in flight.

The findings just outlined provide the basis for a specification of high-frequency aircraft liaison antennas for use by the military services. This specification requires essentially that a proposed antenna perform equally well or better than the reference fixed-wire antenna. Proof of performance is almost entirely based on preliminary measurements which do not require a complete, full-scale aircraft.

The specification insures satisfactory performance of the aircraft antenna systems. Because of the close relationship between high-frequency antenna characteristics and the size and shape of the airframe, the optimum practical antenna system will differ in performance from the minimum allowed by the specification, by amounts equivalent to changes in signal power of, usually, less than 3 db. Changes in system performance due to increases or decreases in signal power of this magnitude are usually small compared to the changes produced by factors other than the antennas. The choice of a frequency of transmission below the optimum value for the path, for instance, may cause losses in intelligibility of communications offsetting many times any gains produced by careful antenna design. Of equal importance is the strict adherence to proper operating procedures. This is, of course, closely related to the necessity of adequate training of the operators, both on the ground and in the air. As an example, severe reductions in articulation score can be expected when words outside the standard vocabulary of the system are transmitted.

The Air Force requires communications under conditions where the reliability of any practical communication system will almost always be marginal. The difference between a good antenna system and a poor one may mean the difference between communications and no communications. If the antenna system is designed according to the specification, it will be known that any required improvements of the system must be sought in other parts of the communication system.

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APPENDICES

MILITARY SPECIFICATION
ANTENNAS, LIAISON COMMUNICATIONS EQUIPMENT
GENERAL SPECIFICATION FOR DESIGN OF

PERFORMANCE EVALUATION OF H-F AIRCRAFT ANTENNA SYSTEMS

THE EFFECT OF THE IONOSPHERE ON THE PERFORMANCE RATING
OF H-F AIRCRAFT ANTENNAS

EVALUATION OF H-F AIRCRAFT ANTENNAS FOR RECEIVING

THE MEASUREMENT OF PERFORMANCE OF VOICE-MODULATED
COMMUNICATION SYSTEMS

FLIGHT TESTING OF THE H-F LIAISON SYSTEM

EQUIPMENT FOR MEASURING SIGNAL-TO-NOISE RATIO DISTRIBUTIONS

DIRECT MEASUREMENT OF THE POWER TRANSFER EFFICIENCY
OF LIAISON ANTENNA SYSTEMS

A METHOD OF EVALUATING H-F AIRCRAFT ANTENNAS UTILIZING
SCATTER-SOUNDING TECHNIQUES

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APPENDIX A

MILITARY SPECIFICATION MIL-A-9080(USAF)

ANTENNAS, LIAISON COMMUNICATIONS EQUIPMENT GENERAL SPECIFICATION FOR DESIGN OF*

1. SCOPE

1.1 This specification covers the performance requirements for the design of airborne antennas for use with liaison communication equipment, including the furnishing of engineering reports.

2. APPLICABLE SPECIFICATIONS AND PUBLICATIONS

2.1 The following specifications and other publications, of the issue in effect on the date of invitation for bids, shall form a part of this specification to the extent specified herein.

2.1.1 <u>Specifications</u>:

<u>Military</u>:

MIL-C-71	Connectors "N" For Radio Frequency Cables
MIL-E-3643	Connectors, "HN" For Radio Frequency Cables
MIL-E-5400	Electronic Equipment, Airborne, General Specification For
MIL-R-6471	Radio Set AN/ARC-21
MIL-P-7094	Plastic Parts, Aircraft Exterior, General Requirements and Tests for Rain-Erosion Protection of
MIL-P-8013	Plastic Materials, Glass Fabric Base, Low Pressure Laminated, Aircraft Structural
MIL-A-9094	Arrester, Lightning, Integral Antenna

*This document was prepared by Mr. V. Reese of the Communication and Navigation Laboratory, WADC, in collaboration with Stanford Research Institute.

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U. S. Air Force:

12053 Plastic, Molded Sandwich Construction, Honeycomb Core

2.1.2 Publications:

AMC Manual 5-4, Preparation of Reports

(Copies of specifications and publications required by contractors in connection with specific procurement functions should be obtained from the procuring agency or as directed by the contracting officer.)

3 REQUIREMENTS

3.1 General. The requirements, including material and workmanship, specified in specification MIL-E-5400 are applicable as requirements of this specification.

3.2 Design. The antenna specified herein is to be installed during or after manufacture of the aircraft or as an integral part of the aircraft structure. The antenna is to be used with Radio Set AN/ARC-21 ( ) and may be in physical combination with any other antenna, thus serving two or more equipments. If the antenna is made in combination with another antenna or antennas it shall be possible to operate the equipments simultaneously (in a receiving or transmitting condition) and with no interference, one with the other. The antenna shall be supplied together with the necessary transmission lines, connectors, isolation units, liaison matching network, and filters.

3.2.1 Mechanical.

3.2.1.1 General. The antenna shall consist of an isolated aircraft structure such as a wing tip or vertical stabilizer tip, shunt fed element, notch or other system suitable for installation in aircraft and consistent with the position in which it is to be mounted.

3.2.1.2 Preferred Antenna Configurations. The following basic antenna configurations, listed in order of their preference, are desirable from the standpoint of obtaining a standard coupler of the type now being produced: (see paragraph 6.3)

(a) Isolation of the top portion of the vertical stabilizer.
(b) Isolation of either wing-tip.

If an antenna configuration is proposed which would require the development of a different antenna coupler than the one being produced, the contractor shall demonstrate to the satisfaction of the contracting officer that the proposed antenna is the only design suitable for installation on the aircraft in question or that it is much superior to any other design.

3.2.1.3 Collection of Liquids. The antenna shall be so designed and installed that no water or other liquid can collect in any portion of the antenna when the aircraft is on the ground or in flight.

3.2.1.4 Icing. The antenna shall be constructed to withstand the most severe icing conditions encountered in flight. The antenna shall be designed to minimize undesirable performance effects due to icing.

3.2.1.5 Dielectric Material. The contractor shall submit a process specification in accordance with Specification MIL-P-8013 or Specification No. 12053, covering the manufacturing and fabricating process and methods of control of manufacturing variables of any plastic material used in the construction of the antenna. This process specification shall be in addition to any approved general process specification the contractor may now have and shall be subject to the approval of the Procuring Agency.

3.2.1.5.1 Erosion Resistance. Plastic materials used in the fabrication of any part of the antenna shall meet the resistance to rain erosion requirements of Specification MIL-R-7094 or all exterior plastic parts shall be protected with an erosion resistant material so that the combination shall meet the requirements of Specification MIL-P-7094 and Specification MIL-P-8013.

3.2.1.5.2 External Radii of Curvature (Cap Type Antennas). The conducting portion of the antenna structure shall be designed to provide large, smooth radii of curvature on all external edges and corners, to reduce precipitation static caused by DC corona discharges. If sharp trailing edges and corners are required for aerodynamic reasons, the airfoil may be completed by insulating material attached to the metal of the antenna structure. Radii of curvature of the antenna metal shall not be less than one half inch.

3.2.2 Electrical:

3.2.2.1 General. The antenna system shall be designed to operate satisfactorily over the frequency range from 2 to 24 megacycles per second and to receive and transmit radio communication signals essentially omnidirectional in azimuth.

3.2.2.2 Antenna System Efficiency. The antenna system efficiency of the proposed antenna (see paragraph 6.4.1) shall be determined for the following frequencies: 6, 8, 10, 12, 14, 16, 18, 20, 22 and 24 megacycles per second. The antenna system efficiency shall be at least 50 percent of the antenna system efficiency for the reference antenna (specified in 4.3.2 of this specification) at each of the above frequencies. The average of the antenna system efficiencies at the above frequencies for the proposed antenna shall be no less than that for the reference antenna.

3.2.2.3 Power Transfer Efficiency. The power transfer efficiency of the proposed antenna system (see paragraph 6.4.2) shall be no less than 25 percent at any frequency below 6 megacycles and above 2 megacycles per second. The average power transfer efficiency over the frequency range of 2 megacycles per second to 6 megacycles per second shall be at least 60 percent. These requirements for power transfer efficiencies must be met only at those frequencies within the above range, for which the length of the path from the top of the vertical stabilizer along the front of the fin and top centerline of the aircraft to the leading edge of the wing root and thence along the wing leading edge to the tip exceeds 0.25 wavelengths.

3.2.2.4 Antenna Matching Unit.

3.2.2.4.1 General. An impedance matching unit shall be provided to transform the antenna impedance to a value that will give a voltage standing wave ratio of 2 to 1, or less, on the 50 ohm coaxial transmission line between the transmitter and the antenna. The contractor shall prepare a specification covering the detail requirements for a satisfactory impedance matching unit. If at all possible, the matching unit referred to in paragraph 6.3 shall be used. The specification shall be subject to the approval of the Procuring Agency.

3.2.2.4.2 Matching Unit Efficiency. The power transfer efficiency of the matching unit (see paragraph 6.4.3) shall be the highest obtainable consistent with good engineering practice.

3.2.2.4.3 Impedance Matching Ability. The matching unit shall be capable of automatically matching the antenna impedance including the tolerance specified in 4.4.2.5, using only the information provided by the radio transmitter, and within a time limit not to exceed 10 seconds.

3.2.2.4.4 Voltage Standing Wave Ratio. The design and installation of the antenna and matching unit shall be such that the voltage standing

wave ratio produced on any part of the coaxial cable between the transmitter and the antenna matching unit shall not exceed 2 to 1 when the liaison equipment is transmitting at any frequency within the 2 to 24 megacycles per second range.

3.2.2.5 Lightning Protection. The antenna shall be provided with a lightning arrester, designed in accordance with Specification MIL-A-9094 (USAF) to protect the antenna and associated equipment from damage due to lightning strokes.

3.2.2.6 Rf Corona and Voltage Breakdown. The proposed antenna shall be so designed that no evidence of corona or voltage breakdown shall occur at the maximum altitude of the aircraft when a voltage 50 percent in excess of the maximum calculated peak voltage is applied across the antenna input terminals. The maximum peak voltage shall be based on the maximum peak modulated power delivered to the antenna terminals at the frequency where the impedance is such that the gap voltage is greatest.

3.2.2.7 Transmission Line and Connectors. The antenna shall be so designed and installed that connection can be readily made to the associated radio equipment through the shortest practical length of rf coaxial cable using appropriate transmission line connectors specified in Specification MIL-C-71 or MIL-C-3643.

3.2.2.8 Selective Isolating Devices. If the proposed liaison antenna is to be used in combination with another antenna or antennas in a multiplexing system, the contractor shall provide the necessary isolation units and filters required for satisfactory operation of all the equipments involved. The contractor shall submit a specification covering the design and fabrication of each isolation unit necessary to provide satisfactory multiplexing of the equipments. The specification shall be subject to the approval of the Procuring Agency.

3.3 Required Measurements.

3.3.1 Radiation Pattern Measurements. The contractor shall obtain the radiation patterns of the proposed antenna at full scale frequencies of 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, and 24 megacycles per second and the radiation patterns of the reference antenna (specified in 4.3.2 of this specification) at frequencies of 6, 8, 10, 12, 14, 16, 18, 20, 22, and 24 megacycles per second. The methods of measurement shall be as specified herein.

3.3.2 Impedance.

3.3.2.1 General. The impedance of the proposed antenna shall be measured over the full scale frequency range of 2 to 24 megacycles per second. The initial measurements shall be made on a scale model of the aircraft for the purpose of arriving at a satisfactory electrical design prior to installation of the antenna on a full scale aircraft. Full scale measurements shall be made on the prototype antenna installation for comparison with the model impedance data

3.3.2.2 Model Measurements. The impedance of the proposed antenna shall be determined over the full scale frequency range of 2 to 24 megacycles per second by installing the antenna on a scale model of the aircraft for which it is being designed. The impedance of the antenna shall be measured at model frequencies corresponding to full scale frequency intervals of 1 megacycle over the frequency range of 2 to 24 megacycles per second. The measurements shall be made at more frequent intervals where it is necessary to establish the minimum or maximum values of resistance or reactance in the above frequency range. The methods of measurement and the test conditions shall be as specified herein.

3.3.2.3 Full Scale Aircraft Measurements. The impedance of the proposed antenna shall be measured over the frequency range from 2 to 24 megacycles per second in 1 megacycle intervals or less with the antenna installed on the full scale aircraft. Measurements shall be made with the aircraft in at least two different locations, for example, on reinforced concrete, non-reinforced concrete, or off the runway. The methods of measurements shall be as specified herein.

3.3.3 Antenna Efficiency. For "cap" type antennas the antenna efficiency (see paragraph 6.4.4) shall be determined over the frequency range from 2 to 6 megacycles per second from the dielectric loss of the plastic isolating section as specified herein. For frequencies above 6 megacycles per second it must be demonstrated that the antenna efficiency is essentially unity. If an antenna is proposed other than a "cap" type the contractor shall submit to the Procuring Agency a proposal of the method to be used in determining antenna efficiency.

3.3.4 Matching Unit Efficiency. The power transfer efficiency of the antenna matching unit together with the transmission line from the transmitter shall be determined as specified herein.

3.3.5 Corona and Voltage Breakdown. Tests for protection against corona and voltage breakdown shall be made in accordance with 4.4.8 of this specification.

3.3.6 Operational Flight Tests. The antenna system shall be flight tested using at least ten frequencies spaced through the range of 2 to 24 megacycles per second. Satisfactory voice communication shall be demonstrated over the maximum range for the frequency involved. At least one test shall be made over a distance greater than 2000 miles. The flight test procedure shall be in accordance with 4.4.9 of this specification.

3.4 Engineering Reports.

3.4.1 Preliminary Report. A preliminary letter report shall be submitted describing the intent, method of approach, general outline, and target date.

3.4.2 Interim Report. A letter report shall be submitted, describing any change in method, antenna program, or target date as soon as such information is known.

3.4.3 Substantiating Data. Data from each of the measurements used to design and test the antenna shall be submitted to the contracting officer as soon as practicable after each test is completed. The method of measurement shall be described and the results shall be clearly presented. In particular, the following data shall be submitted at the time indicated:

3.4.3.1 Preliminary Design Data.

3.4.3.1.1 Principal plane radiation patterns and the corresponding radiation pattern efficiencies for both the proposed and the reference antennas at each frequency of pattern measurements shall be submitted when the pattern measurements are completed.

3.4.3.1.2 The impedance characteristics of the proposed antenna shall be submitted when the model measurements are completed.

3.4.3.1.3 As soon as the model impedance data has been obtained, a preliminary estimate of antenna efficiency shall be submitted.

3.4.3.1.4 A corrected curve of the antenna impedance based on the model impedance data and the estimated shunt capacitance and shunt conductance of the dielectric material to be used in the gap shall be submitted with the preliminary estimate of antenna efficiency.

3.4 3.1.5 A preliminary estimate of coupler efficiency shall be obtained from the corrected antenna impedance and shall be submitted with the preliminary estimate of antenna efficiency.

3.4 3.1.6 An estimate of the peak rf voltage which will appear across the antenna gap at the frequency for which this voltage will be the highest shall be submitted. This estimate shall be based on the corrected antenna impedance and on the estimated coupler efficiency assuming 150 watts of rf power available at the transmitter and 100 percent modulation. This estimate shall accompany the preliminary estimate of antenna efficiency.

3.4.3.1.7 A computation shall be made based on the preceding design data and estimates to show that the proposed antenna will meet the requirements for antenna system efficiency and power transfer efficiency of this specification. The computation shall take into account the power dissipated in the transmission line between the transmitter and the antenna coupler. This computation shall be submitted as soon as the model pattern and impedance measurements have been completed.

3.4.3.2 Final Design Data. As soon as possible after the antenna and isolating gap have been designed the following data shall be submitted:

(1) Detail drawings of the proposed antenna and isolating gap.
(2) Final estimate of antenna efficiency based on full scale mockup of gap region (for cap-type antennas).
(3) Corrected impedance data based on model impedance and the added shunt capacitance and dielectric losses measured on the full scale mockup of the gap region.
(4) Measured transfer efficiency of the transmission line and antenna coupler.
(5) An estimate of the peak rf voltage which will appear across the isolating antenna gap at the frequency for which this voltage will be highest. (This estimate shall be based on the measured transmission line and coupler efficiency and the corrected model impedance assuming 150 watts of rf power available at the transmitter and 100 percent modulation.)
(6) Altitude chamber measurements of the rf breakdown voltage of the isolating gap at the highest altitude which the aircraft is designed to attain.

3.4.3.3 Data from Prototype Antenna Installed on Aircraft. As soon as practicable after an aircraft with the prototype antenna is completed the following data shall be submitted:

(1) Full scale impedance measurements with the aircraft on the ground.

(2) Data from the flight test required by this specification.

3.4.3.3.1 Flight test reports must describe each test flight conducted by the contractor and comment on any operating defects encountered and modifications found necessary.

3.4.4 Final Engineering Report. A final engineering report prepared in accordance with AMC Manual 5-4, shall be submitted not later than 60 days after release of engineering design data. The final engineering report shall contain the following: (1) construction details of the antenna, including photographs, and (2) a copy of all test data required by this specification, together with a description of the method employed in obtaining the data. Sixty copies of the report, two of which must be reproducible, shall be furnished to the Procuring Agency by the Contractor.

4. SAMPLING, INSPECTION, AND TEST PROCEDURES

4.1 The antenna shall be subject to inspection by authorized Government inspectors. When inspection is conducted at the contractor's or manufacturer's plant, tests shall be conducted by the contractor or manufacturer under the supervision of the authorized Government inspector.

4.2 Previous acceptance or approval of material or the release of any design by the Procuring Agency shall in no case be construed as a guarantee of acceptance of the finished product.

4.3 Test Conditions.

4.3.1 Equipment Required.

Boonton, Type 160-A Q-Meter or equivalent
General Radio Type 916A RF Bridge or equivalent
General Radio Type 1601 RF Bridge or equivalent
General Radio Type 1602A Admittance Meter or equivalent
Bridge Detector, Battery Operated, 2 to 24 Mc
Bridge Detector, Battery Operated, 10 to 250 Mc
Bridge Oscillator, Battery Operated, 2 to 24 Mc
Bridge Oscilator, Battery Operated, 10 to 250 Mc
Pattern Range to cover the model frequencies
Scale Models 1/20th to 1/50th scale for pattern measurements, 1/5th to 1/10th scale for impedance measurements.
Radio Set AN/ARC-21

4.3.2 Reference Antenna. The reference antenna required in this specification shall consist of a fixed-wire extending from an insulator connected to the center tail fin, or in the case of double tail fin aircraft, from either the right or left tail fin whichever is the more convenient, to an insulator on the top center line of the fuselage. The wire shall be sixty-five feet in length or 80 percent of the fuselage length whichever is shorter. The antenna shall be suspended from the tip of the tail fin provided that the angle between the fuselage and antenna is less than 15 degrees. If this angle is larger the point of suspension shall be lowered so that the angle equals 15 degrees. The feed point shall be at the forward end of the antenna.

4.3.3 Model Impedance Measurements (Test Conditions).

4.3.3.1 The scale model for impedance measurements shall be large enough to contain all of the measuring equipment. It shall not be smaller than 1/10th scale nor larger than 1/5th scale and shall be covered with good conducting material.

4.3.3.2 All required measurements shall be made with the model in the clear, at least 30 feet away from surrounding objects and at least 25 feet off the ground. It shall be supported by a dielectric structure.

4.3.3.3 All the measuring equipment shall be installed inside the model and the primary supply voltage for this equipment shall be obtained from a source contained within the model. No external power leads or wires of any nature shall be connected to the model.

4.3.3.4 Final adjustment of the measuring equipment shall be made with the operator away from the model in a location where he has negligible effect on the antenna impedance. The mechanical means provided for remote adjustment of the equipment shall be constructed of dielectric material. To be sure that the operator is in a position where he has negligible effect, he shall move completely away from the model after the final adjustments have been made; this should produce no appreciable effect on the indicating instruments.

4.3.3.5 It is important that the circuit losses of the section of transmission line and any other network connecting the antenna to the measuring apparatus be small compared to the power absorbed (radiated and dissipated) by the antenna.

4.3.4 Flight Tests (Test Conditions).

4.3.4.1 Airborne Test Station. The airborne test station shall consist of a standard Radio Set AN/ARC-21 installation in the aircraft having the prototype antenna installation. The radio set shall be tuned and adjusted in accordance with the tests for performance in test installations as specified in 4.3.4.3.

4.3.4.2 Ground Test Station. The ground test station shall consist of a Radio Set AN/ARC-21 which has met the tests for performance in test installations, as specified in 4.3.4.3 connected through a minimum length of rf cable RG-8/U to a vertically polarized ground station antenna. All ground station equipment shall be connected and adjusted according to the best installation and operating practice. The ground station standard antenna shall be located on terrain that is reasonably flat and free from objects that would cause radio reflections. The site selected shall be subject to the approval of the Procuring Agency.

4.3.4.3 Radio Set AN/ARC-21 Performance in Test Installations. AN/ARC-21 equipment which satisfactorily meets the operating requirements of Specification MIL-R-6471 shall be considered satisfactory for test installations, except that the Government engineer or inspector assigned to the project shall have the authority to require such additional tests as he considers necessary to assure proper operation of the equipment.

4.3.4.4 Communications Performance. The equipment shall be ground tested after installation in the aircraft or ground stations. Radio Set AN/ARC-21 shall be properly installed and connected in accordance with the Handbook of Maintenance Instructions. In addition, and for the prototype test installation only, a suitable monitoring device shall be employed which will give an indication proportional to the rf power supplied to the antenna. This power meter is to be used to monitor the transmitter output to determine during flight tests that the equipment is operating satisfactorily. The monitoring method shall be subject to the approval of the Procuring Agency.

4.4 Methods of Measurement.

4.4.1 Radiation Pattern Measurements. Radiation patterns of a scale model of the airframe with the antenna installation shall be plotted on a model pattern range. The three principal plane patterns and a set of patterns in which ϕ is variable and θ has the values 0°, 25°, 37°, 45°, 53°,

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60°, 66°, 72°, 84°, 90°, 96°, 102°, 108°, 114°, 120°, 127°, 135°, 143°, 155°, and 180° shall be obtained for both the θ and the ϕ polarizations. (For a definition of these angles see Fig. 1.) These patterns shall be plotted in polar coordinates with relative field strength plotted radially on a linear scale. Care must be taken that all the patterns at a given frequency are plotted to the same scale (i.e., radiated power and detector sensitivity constant for all patterns at a given frequency).

4.4.1.1 Radiation Pattern Efficiency The radiation pattern efficiency for each frequency shall be calculated from the set of radiation patterns as follows:

(1) For each polarization obtain through the use of a planimeter the area enclosed by each of the measured linear polar pattern plots.

(2) For each of the specified values of θ add the two areas from (1), above, corresponding to the two polarizations.

(3) Plot the values obtained in (2) above, as a function of cos θ ($-1 \leq \cos\theta \leq +1$) on a rectangular coordinate chart, and draw a smooth curve through the plotted points.

(4) Obtain with the aid of a planimeter the total area under the curve given by (3) above, between $\theta = 0°$ and $\theta = 180°$.

(5) Obtain with a planimeter the area under the curve given by (3) above and bounded by the straight lines which correspond to the two limiting values of θ, that is $\theta = 60°$ and $\theta = 120°$.

(6) Divide the area obtained in (5) by the area obtained in (4). This ratio is the "radiation pattern efficiency" for the frequency at which the pattern set was measured. It must necessarily lie in the range zero to one.

4.4.2 Impedance Measurements (Model). The contractor shall have the privilege of using any one or any combination of methods to measure the impedance, provided that such methods are appropriate to the frequency range, and to the impedance values being encountered. If the authorized government inspector considers the data obtained from these measurements to be of questionable accuracy, the contractor shall repeat the measurements by any one or any combination of the methods which the inspector shall designate. The following is a list of recommended methods.

4.4.2.1 RF Bridge Substitution Method. With an rf bridge installed in the model and connected to the antenna terminals by a low loss section

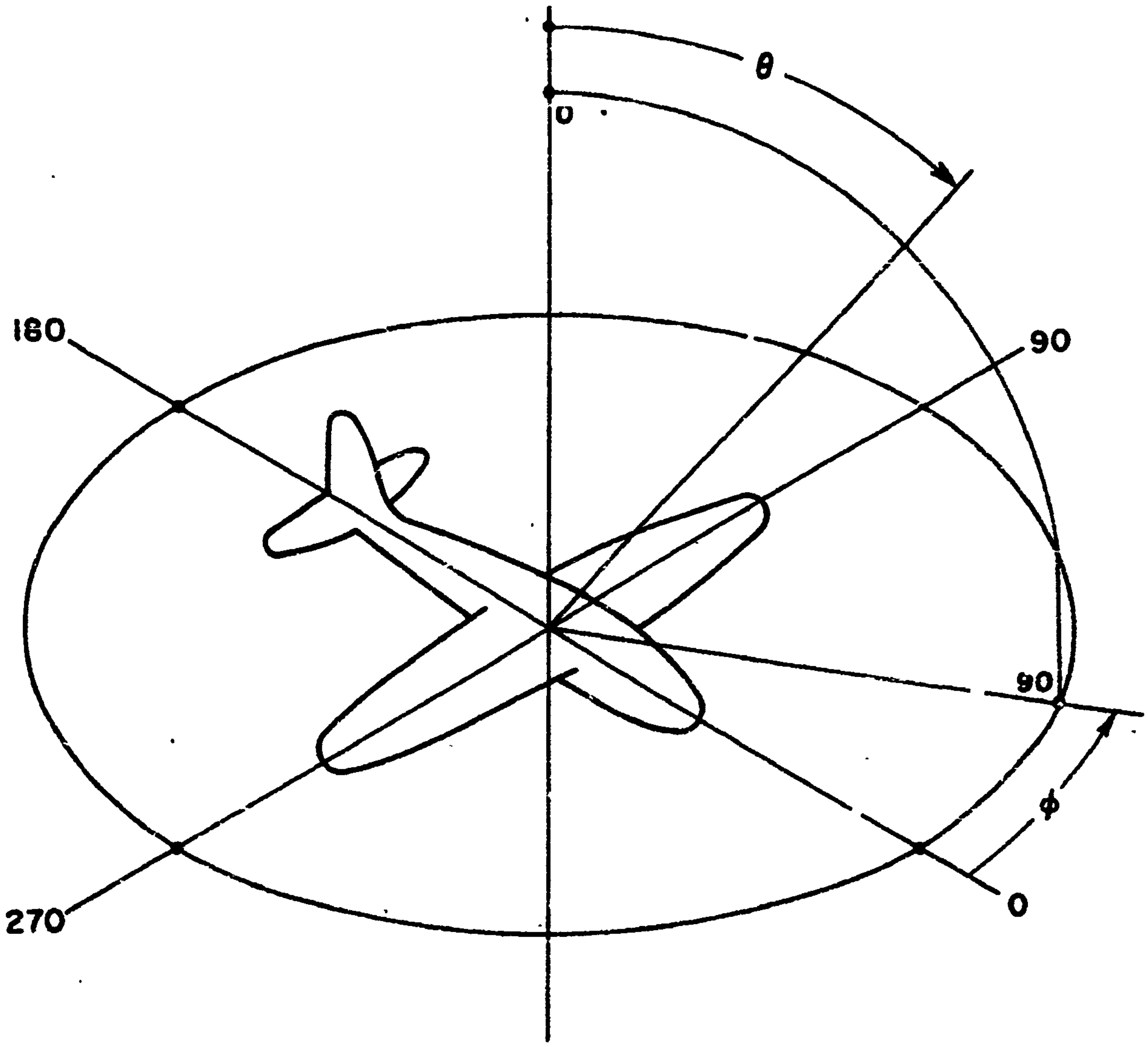

FIG. 1
COORDINATE SYSTEM

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of coaxial transmission line, adjust the bridge to obtain a null. Without altering the bridge settings, remove the antenna from the end of the transmission line and replace it with an adjustable dummy load. Adjust the dummy load until a null is again obtained, then remove it from the transmission line and measure its impedance on an rf bridge.

4.4.2.2 RF Bridge Substitution Method (Partial Match). In using this method of impedance measurement, the procedure outlined in the preceding paragraph is modified as follows. A small low loss matching network is installed at the antenna feed point to provide a more favorable impedance, from the standpoint of rf bridge errors, at the bridge end of the coaxial cable. At each point of the measurement, the matching network is adjusted until a low VSWR is obtained at the rf bridge end of the cable, and the procedure outline in 4.4.2.1 is followed.

4.4.2.3 Direct Method. An rf bridge is installed at the antenna feed point or, if this is physically impossible, at a point within the model where connection to the antenna can be made with a short straight section of low loss air-dielectric coaxial line. The antenna impedance is either obtained directly, or in the case of the coaxial line, calculated from the impedance at the bridge terminals by conventional transmission line transformations. The length of coaxial line must be short in comparison to a wavelength at the frequency of measurement to avoid errors.

4.4.2.4 Susceptance Variation Method. When the linear dimensions of the air-frame are considerably less than a half wavelength, the resistance of a cap-type antenna is very low and the reactance is high. In this case there is no standard measuring instrument suitable for the impedance range, yet small enough to be mounted in the model. To obtain the impedance in such cases a parallel resonant circuit can be constructed and the antenna conductance measured by varying the capacitance (Fig. 2). Both the detector and signal source must be very loosely coupled. The circuit is first resonated without the antenna by adjusting C_0, and the width of the resonant curve between half power points is measured by varying the vernier condenser, C_1, which is in parallel with the main tuning condenser, C. The conductance of the unloaded circuit is $G_l = \omega\Delta C_1/2$ where ΔC_1 is the change in capacitance between half power points. The antenna is then connected and the circuit resonated again by adjusting C_0 with C_1 returned to its initial position. The change in C_0 is the capacity of the antenna,

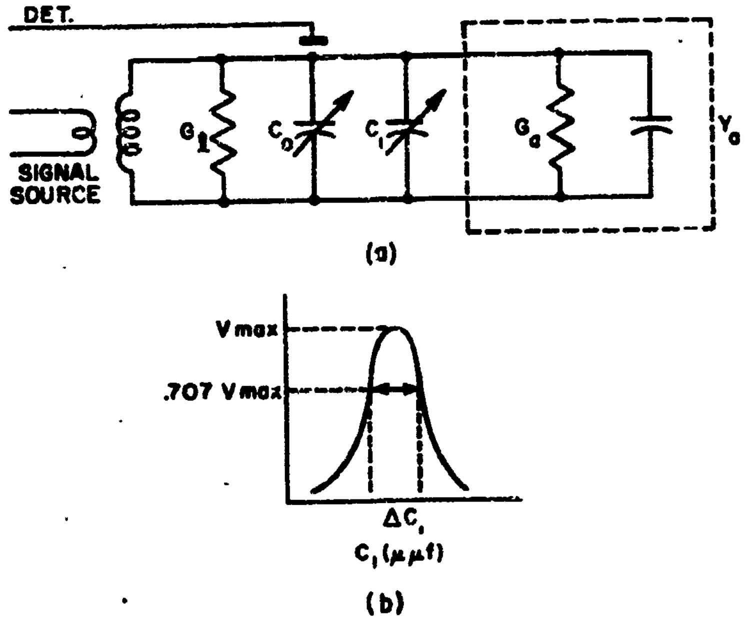

FIG. 2

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and the width of the resonant curve is obtained in the same manner as before. The conductance of the loaded circuit is $\omega\Delta C_1/2 = G_t + G_a$. A limitation on this method results from the fact that the antenna conductance, G_a, in some cases is as small as 1 micromho, while the susceptance is of the order of 1000 micromho, so that even with coil Q's of 300 or 400, G_t is large compared to G_a. To overcome this difficulty, a vacuum tube circuit which is equivalent to a negative conductance can be added to raise the Q of the circuit. Stable Q's of the order of 1000 to 2000 can be obtained in this manner.

4.4.2.5 Nominal Impedance Curve. Plot a nominal antenna impedance curve based on the measured model impedance data. The following tolerance shall be placed on the nominal impedance values for the purpose of matching unit design.

a. Resistance ± (20% + 1 ohm)
b. Reactance ± 20%

4.4.3 Full Size Aircraft Impedance Measurements. The General Radio Type 916A RF Bridge or equivalent together with the Bridge Oscillator and Bridge Detector shall be installed inside the aircraft fuselage at any convenient location for performing the measurements. Connection from the rf bridge to the antenna feed point shall be made through a length of RG-8/U coaxial cable. The aircraft shall be in the clear with no connecting wire attached. Primary power for operation of the bridge oscillator and detector shall be obtained from a source within the aircraft. Measurements can be made by one of the methods described, in par. 4.4.2, or other suitable methods may be used.

4.4.4 Antenna Efficiency.

4.4.4.1 General. The method for estimating antenna efficiency described below apply to cap-type antennas only. For other types of antennas these estimates must be made by appropriate methods, and the methods used are subject to approval by the Contracting Officer.

4.4.4.2 Preliminary Estimate. Measure the capacity and Q of the configuration shown in Fig. 3 with and without a slab of the dielectric material proposed for use as skin of the gap. This configuration shall consist of a rectangular sheet metal plate of height approximately equal to the

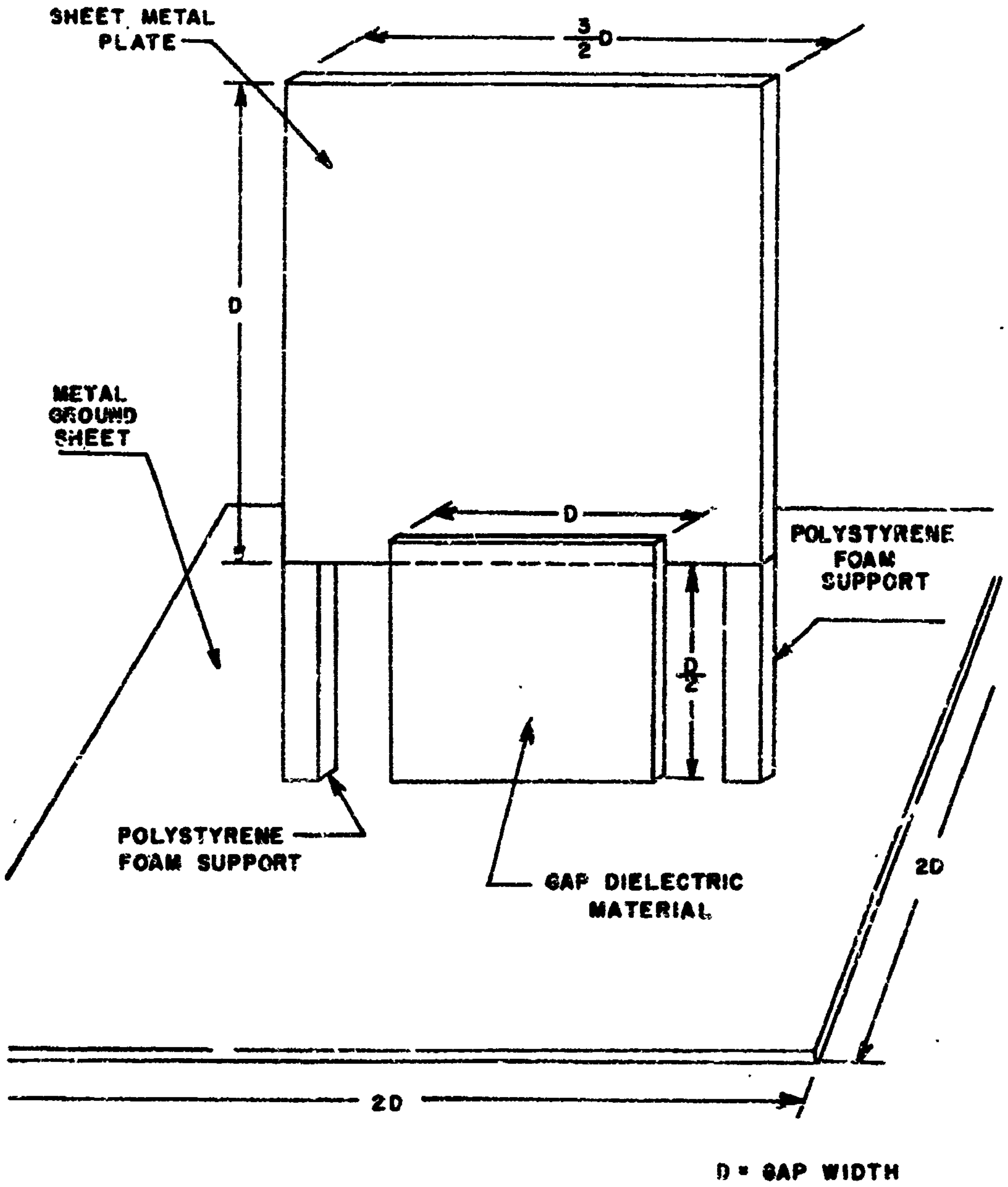

FIG. 3
CONFIGURATION FOR PRELIMINARY ESTIMATE OF ANTENNA EFFICIENCY

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proposed gap width, and about 1½ gap widths wide. It shall be supported ½ gap width above a square ground sheet by means of two foam polystyrene supports. The sides of the ground sheet shall be at least two gap widths long. The slab of dielectric material shall rest on the ground sheet and be fastened to the metal plate in a convenient manner. The edges of the dielectric slab shall be sealed in the manner proposed for construction of the actual gap. Fiber orientation of the dielectric material shall be in the same direction as in the proposed version of the antenna.

4.4.4.2.1 Measurements shall be made using a Boonton type 160-A Q-meter or equivalent. Enough data shall be taken to establish the curve in the frequency range 2 to 6 megacycles per second, but at least one point shall be determined in every 0.5 megacycles. The Q-meter shall be placed off to the side of the gap near one of the supports. It shall be securely grounded to the ground sheet which, in turn, shall be grounded to a water pipe or other good ground connection. The leads to the meter shall be as short as practical.

4.4.4.2.2 A second set of measurements shall be made after immersing the dielectric slab in tap water for 72 hours. The slap shall then be removed from the water and wiped dry and allowed to dry further for five minutes at room temperature, before repeating the measurement described above. Measurements shall start at the lowest frequency and be taken for increasing frequencies. All measurements shall be completed within one hour after removing slab from water.

4.4.4.2.3 From these measurements the added shunt admittance due to the dielectric skin material in the gap shall be estimated as follows:

Let C_0 = Capacity in microfarads required to resonate Q-meter coil without external connection.

Q_1 = Q as read off instrument with plate attached but without dielectric slab.

Q_2 = Q as read off instrument with plate attached and with dielectric material.

ΔC = Change in capacitance in microfarads, read off vernier dial with plate attached, with and without dielectric slab.

f = Frequency in Mc/sec.

L = Peripheral distance around gap in feet.

D = Gap width in feet (distance from isolated metallic section to main part of airframe).

Then the added shunt admittance (mhos) across the gap due to the dielectric skin is then given by $Y_d = G_d + jB_d$, where

$$G_d = 2\pi f\, C_0 \left(\frac{1}{Q_2} - \frac{1}{Q_1}\right)\frac{L}{2D} \text{ mhos}$$

$$B_d = 2\pi f \Delta C \frac{L}{2D} \text{ mhos}$$

4.4.4.2.4 The effect of dielectric spar sections upon gap admittance shall be determined by measuring the dielectric constant and loss tangent of a sample of the spar material using conventional techniques. Measurements shall be taken before and after soaking as specified for the skin material. During the measurements the sample shall be oriented so that the glass fibers are lengthwise in the field. The admittance of the spar sections shall be calculated from the dielectric constant and loss tangent assuming uniform electric fields in the gap. This admittance shall be added to the skin admittance to determine the total effect of the dielectric isolating section.

4.4.4.2.5 These results shall be used for correcting the model antenna impedance as required in 3.4.3.1.4 of this specification, as well as for estimating the antenna efficiency. For correcting the model impedance at frequencies above 6 megacycles it may be assumed that $Y_d = jB_d = j2\pi f \Delta C (L/2D)$ where ΔC is that measured at 6 megacycles per second. To show that this is a reasonable assumption, the dielectric constant and loss factor of the dielectric material shall be measured in any convenient manner over the frequency range from 2 to 24 megacycles per second.

4.4.4.3 Final Estimate. For these measurements a full size mockup of the gap and surrounding aircraft structure shall be built. The same mockup as required in 4.4.8 may be used.

4.4.4.3.1 The capacity and Q across the antenna gap shall be measured with the isolated cap supported by polystyrene foam at the proper distance. Measurements shall be made using a Boonton type 160-A Q-meter or equivalent. Enough data shall be taken to establish the curve in the frequency range from 2 to 6 megacycles per second but at least one point shall be determined in every 0.5 megacycles.

4.4.4.3.2 The above measurements shall be repeated with the complete gap structure proposed for the final version of the antenna, including

fiberglas laminate panels and supports, lightning protective devices, isolation units, connectors and any other equipment which will be placed in the gap.

4.4.4.3.3 These data shall be used to compute antenna efficiencies and to correct the impedance measurements of section 4.4.2 as required in 3.4.3.2 of this specification.

4.4.5 <u>Matching Unit Measurements</u>.

4.4.5.1 <u>Estimate of Power Transfer Efficiency of Matching Unit.</u> The efficiency of the impedance matching unit shall be estimated by use of the charts, Figs. 4 and 5. The procedure for using these charts is as follows:

(1) The antenna impedance shall be normalized to the characteristic impedance of the transmission line from the transmitter to the matching unit.

(2) For frequencies between 2 Mc and 15 Mc use the chart of Fig. 5. Find the point corresponding to the normalized antenna impedance on the chart. The matching circuit efficiency shall be obtained by interpolation between contours of constant efficiency (η = constant).

(3) At frequencies above 15 Mc proceed in the same fashion using the chart of Fig. 2.

4.4.5.2 <u>Measurement of Power Transfer Efficiency of Matching Unit and Transmission Line</u>. The power transfer efficiency of the transmission line and antenna matching unit shall be measured together; this efficiency is the product $\eta_t \eta_c$. It is the ratio of the power input at the antenna terminals to the power input at the coaxial line between the transmitter and antenna.

4.4.5.2.1 The contractor shall have the privilege of using any one or any combination of methods to measure the efficiency of the matching unit and transmission line, provided such methods are appropriate to the frequency range and to the impedance values of the antenna. If the authorized government inspector considers the data obtained from these measurements to be of questionable accuracy, the contractor shall repeat the measurements by any one or any combination of methods which the inspector shall designate. The following is a list of recommended methods:

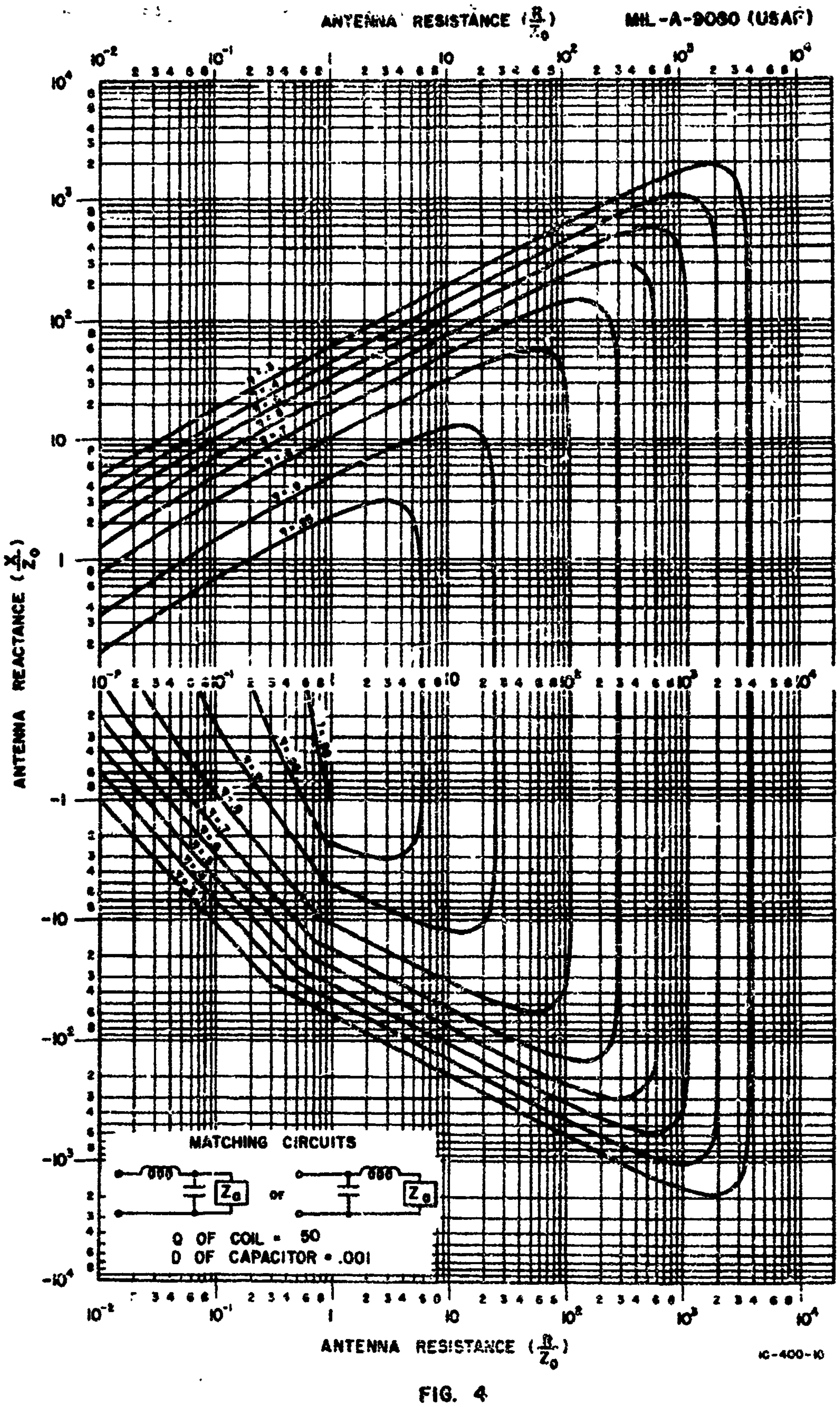

FIG. 4

MATCHING CIRCUIT EFFICIENCY FOR FREQUENCIES ABOVE 15 MC

4.4.5.2.2 Three Impedance Method. In this method the matching unit shall be terminated in a dummy load whose impedance shall be that of the antenna at the frequency of measurement. The dummy load shall be constructed so that most of the power is dissipated in a single resistor, R_0. An rf power source shall be applied to the transmission line and the matching unit allowed to complete its normal tune-up cycle. The input shall be then disconnected from the rf source and connected to an impedance bridge. Three impedances shall be measured: For the first of these, Z_1, the dummy load shall be in the normal condition. The second impedance shall be measured with the resistance component of the dummy load shorted out, designate this Z_2. The third impedance, Z_3 shall be measured with the resistance component opened. The diagrams of Figs. 6A, 6B, and 6C illustrate these measurements. The ratio of the power dissipated in R_0 to the power input to the transmission line is

$$\eta_c \eta_t \eta_e = \frac{|(Z_1 - Z_3)(Z_1 - Z_2)|}{R_1 \; |Z_2 - Z_3|}$$

where η_e is the transfer efficiency of the reactive part of the dummy load, and R_1 is the resistive part of Z_1. If the dummy load is carefully constructed η_e can be made approximately equal to unity, and the formula above yields the product $\eta_c \eta_t$ directly. In any case η_e can be measured by the method outlined above. To determine η_e the dummy load is connected directly to the bridge. Hence

$$\eta_e = \frac{|(Z_1{'} - Z_3{'})(Z_1{'} - Z_2{'})|}{R_1{'} \, |(Z_2{'} - Z_3{'})|}$$

where the primes indicate measurements made with the dummy load alone.

4.4.5.2.2.1 For cap-type antennas a dummy load built according to the schematic diagram of Fig. 6A is suitable. With care in construction the losses in the reactive elements can be made negligible. The resistor, R_0, shall have sufficient power dissipating capacity to absorb the power applied to the load during tune-up. It is not necessary to know its impedance, but for accurate measurements its reactance shall not be more than 20 percent of its resistance. Globar high frequency resistors have proved satisfactory. Construction of the reactive part of the dummy load can be simplified if a range of resistance values is employed.

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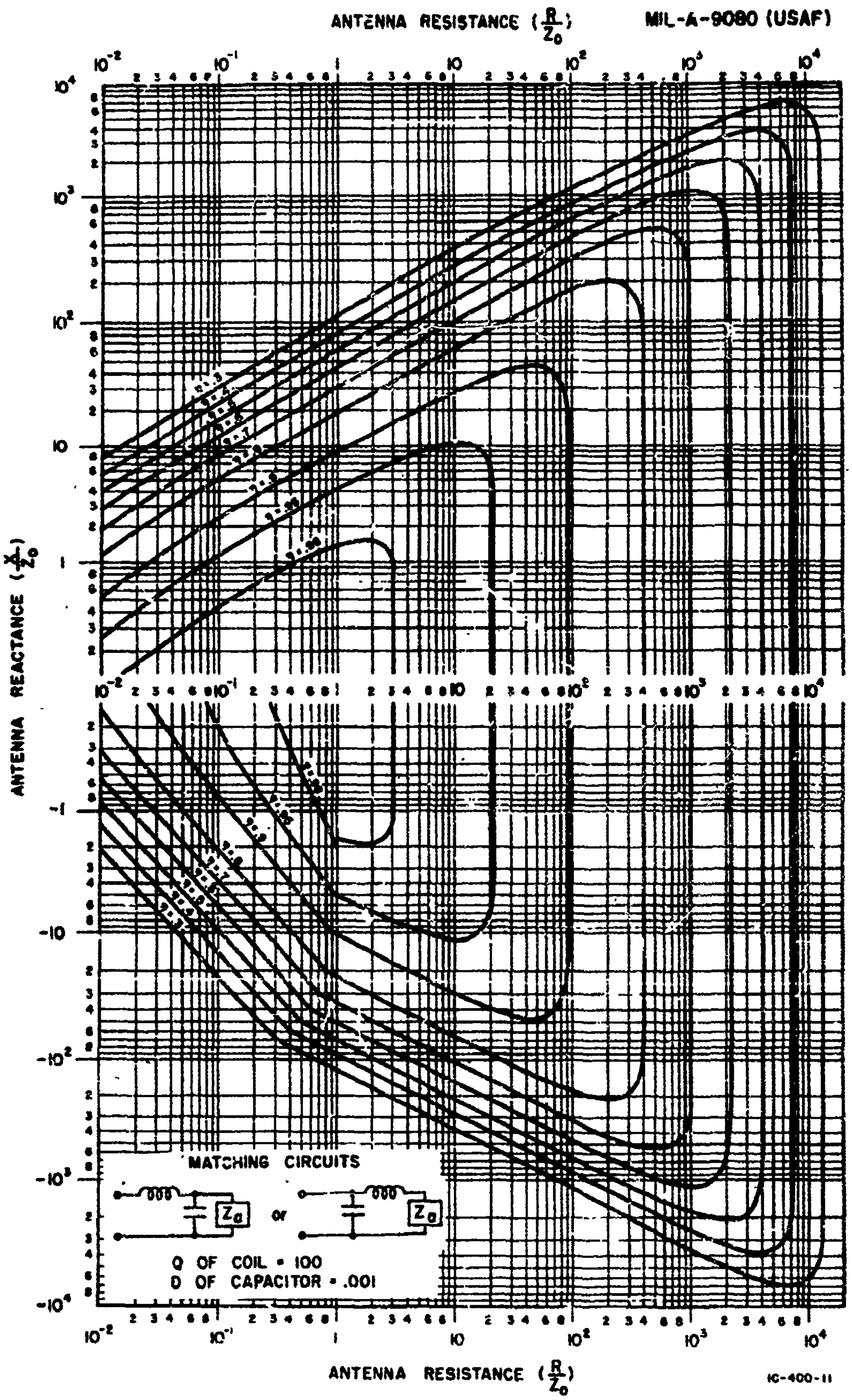
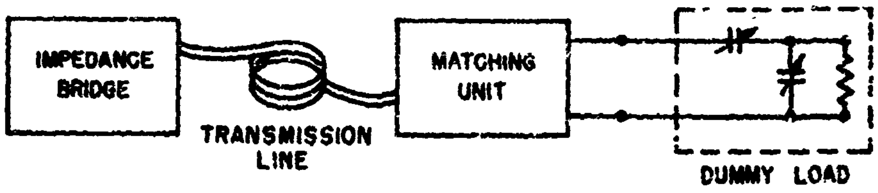
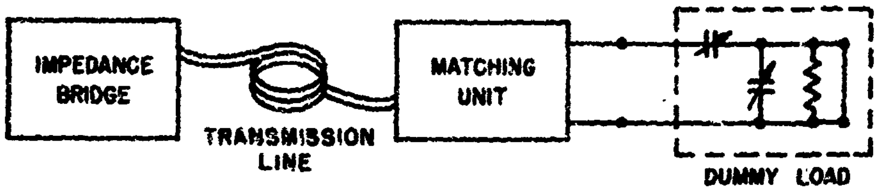


FIG. 5

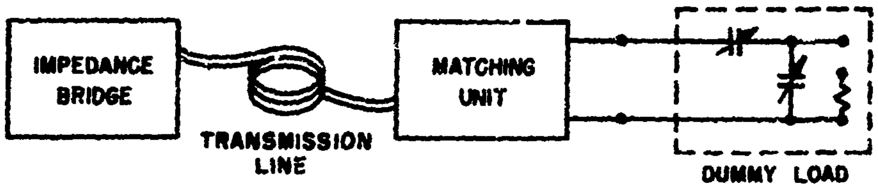
MATCHING CIRCUIT EFFICIENCY FOR FREQUENCIES BELOW 15 MC



MEASUREMENT OF Z_1



MEASUREMENT OF Z_2



MEASUREMENT OF Z_3

FIG. 5

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4.4.5.2.3 Current and Resistance Measurement. The most straightforward scheme requires the measurement of current and resistance at the transmission line input and at the dummy load. The input and output powers are obtained directly. The efficiency $\eta_c\eta_t$ is the ratio of power out to power in. In the current-resistance method the coupler shall be terminated in a dummy load of the proper impedance in series with an rf ammeter. A source of rf power shall be connected to the input of the transmission line through an rf ammeter and the matching unit shall be allowed to complete its normal tune-up cycle. When a match is obtained the input and load currents shall be recorded. The transmission line shall be disconnected from the power source and the impedance shall be measured looking into the line. The output and input power shall be computed (I^2R) . When using this method several precautions must be observed. To obtain the resistance values correctly care must be taken to keep the circuit strays constant during measurement. It should be further noted that the current measurements are subject to considerable error and that a 1% error in current measurement produces a 2% error in computed power. On the input side of the network care must be taken to minimize strays to ground between the current meter and the point at which the matching network input impedance is measured. On the output side of the network it is necessary to make the meter part of the load impedance so that the series impedance of the meter and the strays to ground are accounted for. This is particularly true when measuring wing-cap or tail-cap impedances at 2 megacycles where the antenna resistance may be very low. The meter resistance may then become an appreciable part of the total load resistance. Thus, any change in meter impedance between the bridge measurement and the current measurement may become a source of error. Of more concern than the above considerations, however, is the fact that a number of different meter ranges must ordinarily be used to measure the load current over the 2 to 24 megacycle band because of the variation in antenna resistance. Accurate meter calibration is therefore a necessity.

4.4.6 Antenna System Efficiency. The antenna system efficiency of the proposed antenna shall be computed at each of the frequencies required in 3.2.2.2 of this specification by the following formula: $\eta_s = \eta_p\eta_a\eta_c\eta_t$ where

η_s = ANTENNA SYSTEM EFFICIENCY

η_p = RADIATION PATTERN EFFICIENCY

η_a = ANTENNA EFFICIENCY

η_c = ANTENNA COUPLER EFFICIENCY

η_t = TRANSMISSION LINE EFFICIENCY

η_p shall be computed from the model pattern measurements in accordance with 4.4.1.1 of this specification. η_a normally can be assumed to be unity in the frequency range of 6 to 24 megacycles per second, however, the contractor shall demonstrate that this is essentially true. The products of $\eta_c\eta_t$ is the measured value of efficiency for the combined transmission line and antenna coupler measured in accordance with 4.4.5.2 of this specification.

4.4.6.1 For the reference antenna it shall be assumed that $\eta_a = 0.9\eta_p$. The antenna system efficiency shall meet the requirements of 3.2.2.2 of this specification.

4.4.7 Power Transfer Efficiency. The power transfer efficiency of the proposed antenna shall be computed and a curve of efficiency vs frequency shall be plotted over the frequency range 2 to 6 megacycles per second. Enough points shall be computed to establish the curve but at least one point shall be computed every 0.5 Mc.

4.4.7.1 The following formula shall be used to compute the power transfer efficiency of the proposed antenna: Power transfer efficiency $= \eta_a\eta_c\eta_t$ where η_a is the antenna efficiency estimated in accordance with 4.4.4. η_c is the power transfer efficiency of the matching unit, and η_t is the power transfer efficiency of the transmission line. η_c and η_t shall be determined in accordance with 4.4.5.2 of this specification.

4.4.7.2 The calculated power transfer efficiency shall meet the requirements specified herein.

4.4.8 Corona and Voltage Breakdown. The antenna installation including lightning arrester, lead in, and isolation units if used, shall be tested for protection against corona and voltage breakdown. The tests shall be performed at simulated maximum altitude in an altitude chamber, using full scale mockups of the vulnerable regions of the antenna installation. Vulnerable points which shall be tested are the regions where application of the principals of electrostatic field theory indicates the probable presence of high voltage gradients. For isolated tip antennas such vulnerable points include spar splice regions, hinge joints, angular breaks

in the isolating gap, leading and trailing edge, etc. Tests can be made using a mockup of the entire gap region or, alternatively, they can be made using sectional mockups of the regions of interest provided that the section tested includes enough of the structure on either side of the point of interest to insure the similarity of electric fields at the point under test.

4.4.8.1 The rf voltage for breakdown or corona onset shall be established as follows: At the simulated altitude (maximum and operational), the rf voltage applied to the mockup shall be increased until corona or voltage breakdown occurs. The ambient air temperature of the pressure chamber during the test shall be recorded. The rf voltage which causes the onset of corona or voltage breakdown shall be corrected to minus 40 degrees C ambient air temperature. The frequency used for this test shall be that at which maximum voltage is developed at the terminals of the proposed antenna. The measurements shall meet the requirements specified herein.

4.4.9 Flight Test Procedure. Under the conditions specified in 4.3.4 of this specification the contractor shall demonstrate satisfactory air-to-ground and ground-to-air voice communication at various altitudes up to the service ceiling of the aircraft and distances from the ground station up to 2000 miles. Test frequencies to be used for a given distance and time of day shall be in accordance with the predictions of the Central Radio Propagation Laboratory. National Bureau of Standards. At least ten frequencies spaced over the frequency range of 2 to 24 megacycles per second shall be used. Frequency authorization can be obtained from the Procuring Agency. At least one test shall be made with the aircraft at a distance greater than 2000 miles from the ground station. Information on ground station facilities for the long range test can be obtained from the Procuring Agency. For each test frequency used the contractor shall demonstrate that satisfactory voice communication can be established at any aircraft heading.

4.4.9.1 Radio Noise. Qualitative noise reception shall be recorded during the tuning operation cycle of the matching unit.

4.4.9.2 Precipitation Static. Qualitative receiving checks during the course of the operational flights tests shall be recorded.

5. PREPARATION FOR DELIVERY

5.1 Not applicable.

6. NOTES

6.1 Use. The antennas covered by this specification are intended to be installed on aircraft and used with high frequency communication equipment.

6.2 The following publication may be of interest in connection with tests specified herein:

Handbook for Maintenance Instructions for Radio Set AN/ARC-21.

6.3 A satisfactory antenna impedance matching unit for use with wing-cap and tail-cap liaison antennas has been developed by Engineering Research Associates, Inc., St. Paul, Minnesota.

6.4 Definitions:

6.4.1 Antenna System Efficiency. Antenna system efficiency is defined as the ratio of the power radiated into the solid angle included between 30 degrees above the horizontal plane through the aircraft to 30 degrees below this plane to the total power input at the transmission line terminals.

6.4.2 Power Transfer Efficiency. Power transfer efficiency is defined as the ratio of total radiated power to the power input to the transmission line at the transmitter terminals.

6.4.3 Matching Unit Efficiency. Matching unit efficiency is defined as the ratio of the power delivered to the antenna to the power input to the matching unit.

6.4.4 Antenna Efficiency. The antenna efficiency is defined as the ratio of the radiated power to the power input at the antenna terminals.

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APPENDIX B

PERFORMANCE EVALUATION OF H-F AIRCRAFT ANTENNA SYSTEMS

A. INTRODUCTION

Antennas for navigation and communication equipments on modern high speed aircraft form an integral part of the airframe; consequently, estimates of the performance of proposed antenna systems are required at an early stage of the development of a new airframe. In order to determine how well an antenna performs its functions one must define the criteria on which judgment is to be based. Such criteria should lead to numerical factors, associated with the antenna systems, which relate the electrical properties of the system to the operational use of the communication link of which the antenna forms a part. It is important that estimates of the magnitude of these factors be made on the basis of model and mockup measurements, alone, in order that the antenna design may be finalized prior to construction of the airframe.

In this appendix, several methods which lead to numerical factors expressing the relative merit of various h-f antenna systems on the same aircraft are discussed. These factors are functions of the signal-to-noise ratio at the receiving end of the communication link, and are therefore related to each other and to the experimental evaluation of aircraft antenna systems, which is described elsewhere in this report.

In order to compare the various proposed methods of antenna evaluation, an analysis was made of the radiation patterns of five different h-f antennas on a C-54 aircraft, six antennas on a Lockheed Constellation, and three on a B-47 medium bomber. The performance ratings obtained for a given antenna, by the use of the different measures, were then compared as to the consistency of the results obtained. The changes of the ratings caused by varying some of the parameters of the evaluation schemes were also studied. It was found that all of the proposed methods of antenna evaluation lead to essentially equal results. This fact not only makes it possible to rate antennas by the method most convenient from a practical point of view, but also leads to an interpretation of their ratings

in terms of articulation scores which are considered here as a primary measure of system performance. It was also found that some of the parameters required in computing the ratings could be varied over considerable ranges before changing the relative standing of different antennas on the same aircraft. It is often difficult to determine the appropriate magnitude of such parameters, especially where sky-wave propagation is involved. This analysis shows that exact knowledge of these factors is not required for the determination of the relative merit of several proposed antenna systems.

B. AVERAGE INFORMATION CAPACITY AS A MEASURE OF ANTENNA PERFORMANCE

The primary function of any communication system is the transmission of intelligence. Lucke has therefore proposed to measure the effectiveness of an antenna by its influence upon the information-transmission capabilities of the communication system of which it forms a part.[1] A "factor of merit" for antenna systems in this sense is given by the average information capacity of the circuit, the average being taken over all situations under which communication links may take place. Let ζ stand for the aggregate of all the variables on which the signal-to-noise ratio, $\frac{S}{N}(\zeta)$, at the receiving end of the link depends. For the air-to-ground liaison system, these variables are the antenna radiation patterns, the transmitted power, and the atmospheric noise, as well as time, place, distance, and frequency of transmission. The variable ζ is distributed with a probability density, $p(\zeta)$. The average information capacity of the circuit, per unit bandwidth, is then given by[2]

$$\overline{C} = \int p(\zeta) \log_2 \left[1 + \frac{S}{N}(\zeta)\right] d\zeta \tag{B-1}$$

where the integration has to be carried out over the volume for which $p(\zeta)$ is defined, i.e. for the volume for which

$$\int p(\zeta) d\zeta = 1$$

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[1] Winston S. Lucke, An Antenna Evaluation Method, Technical Report No. 17, April 1951, Air Force Contract No. AF 19(122)-78 (SRI Project No. 188); Stanford Research Institute, Stanford, California.

[2] C E Shannon, "Communication in the Presence of Noise," Proc. I.R.E., Vol. 37, pp 10-21; January 1949.

The factor defined by Eq. (B-1) is a function of the system as a whole, not of the aircraft antenna alone. When evaluating antennas therefore, all other components of the circuit must remain unchanged. The rating scheme is then relative, giving the increase or decrease in average information capacity due to the use of different antenna systems.

Extensive numerical work is required to compute the average information capacity for even the simplest case. For sky-wave transmission, where the signal-to-noise ratio depends on a large number of variables, use of such a factor is entirely impractical. Changes in both signal level and noise enter the factor in a complicated manner. Such changes may be due to mismatching of the antennas, variations in ionospheric absorption, or use of different transmitters, as well as changes in the orientation of the transmission path with respect to the aircraft. It is therefore of interest to exami . Eq. (B-1) for possible simplifications.

If the signal-to-noise ratio is always less than unity, we have approximately

$$\overline{C} = 1.44\int p(\zeta)\left[\frac{S}{N}(\zeta) - \left(\frac{S}{N}\right)^2(\zeta) + \cdots\right]d\zeta \qquad \text{(B-2)}$$

The first term in this expansion is the factor of merit discussed in Appendix C.

The approximation of Eq. (B-2) breaks down for signal-to-noise ratios larger than unity. In general, however, let

$$\frac{S}{N}(\zeta) = \left[\overline{\left(\frac{S}{N}\right)} + \frac{S}{N}(\zeta) - \overline{\left(\frac{S}{N}\right)}\right]$$

where the bar indicates average values, i.e.

$$\overline{\left(\frac{S}{N}\right)} = \int p(\zeta)\frac{S}{N}(\zeta)d\zeta. \qquad \text{(B-3)}$$

Substituting in Eq. (B-1),

$$\overline{C} = \log_2\left[1 + \overline{\left(\frac{S}{N}\right)}\right] + \int p(\zeta)\log_2\left[1 + \frac{\frac{S}{N}(\zeta) - \overline{\left(\frac{S}{N}\right)}}{1 + \overline{\left(\frac{S}{N}\right)}}\right]d(\zeta)$$

is obtained. Now assume that the deviation of the signal-to-noise ratio from its average value is small compared to the average value, i.e.

$$\frac{\left|\frac{S}{N}(\zeta) - \overline{\left(\frac{S}{N}\right)}\right|}{1 + \overline{\left(\frac{S}{N}\right)}} << 1 .$$

Expanding the logarithmic term and carrying out the integration, the average information capacity is found to be

$$\overline{C} \cong \log_2\left[1 + \overline{\left(\frac{S}{N}\right)}\right] - 0.72\frac{\overline{\left(\frac{S}{N}\right)^2} - \overline{\left(\frac{S}{N}\right)}^2}{\left[1 + \overline{\left(\frac{S}{N}\right)}\right]^2} \tag{B-4}$$

To test the validity of this approximation, the operations required by Eqs. (B-1) and (B-4) were performed on some radiation patterns of h-f antennas on a C-54 aircraft. The noise, N, and the function, $p(\zeta)$, were taken to be constant for these computations. The integrations were carried out over all directions in azimuth about the aircraft antenna, using various slices of the radiation patterns of 10 degrees width in elevation. Separate computations were made for several values of noise power, the smallest noise power differing from the largest considered by about 20 db. In the mean, the average information capacity evaluated by the use of Eq. (B-4) differed from the correct value computed from Eq. (B-1) by only 0.4%. The maximum error among the thirty cases considered was 3%. Using the first term of Eq. (B-4) only, i.e. letting

$$\overline{C} \cong \log_2\left[1 + \overline{\left(\frac{S}{N}\right)}\right] \tag{B-5}$$

the average error was 8% with a maximum error of 14%. It appears therefore that Eq. (B-5), which depends only on the average signal-to-noise ratio, may be used as an approximation to the average information capacity. It should be noted that as long as this approximation is satisfied, use of the average signal-to-noise ratio as a measure of antenna performance will lead to the same rank order in the comparison of several

antennas as that obtained from use of the average information capacity. The definition of the factor of merit described in Appendix C was based on this equivalence. The radiation pattern efficiency which will be discussed presently is also closely related to the average signal-to-noise ratio.

C. THE USEFUL SOLID ANGLE SECTOR.

A complete discussion of all the factors required in the computation of the performance measure given by Eq. (B-5) is presented in Appendix C. It is shown there, that when comparing the relative merit of various proposed antenna systems, much of the detailed consideration of ionospheric transmission can be neglected without altering the relative standing of antenna systems. Before proceeding with a discussion of other performance measures, therefore, certain simplifications will now be introduced which limit the number of variables to those directly related to the antennas. The evaluation factors will then be expressed in terms of radiation patterns and antenna impedance alone. Only the case of transmission from the aircraft to a ground station will be considered, since for reception on the aircraft differences in antenna systems are of relatively minor importance as shown in Appendix D.

In order to arrive at these simplifications, variations in ionospheric conditions must largely be ignored. Noise will be considered constant for any particular case; it will then play the role of a parameter of the various performance measures. The only changes in signal strength considered are those due to variations in antenna patterns which occur because of changes in the direction of transmission with respect to the aircraft. For a constant heading of the aircraft with respect to the ground station, the signal-to-noise ratio is then fixed. To take account of the true variations in signal-to-noise ratio, its distribution in time should also be considered. As shown in Appendix E, these distributions are stationary about their mean value so that conclusions reached on the basis of a single value of this ratio are representative of those obtained by the use of the entire distribution.

The assumptions made physically correspond to replacing the actual ionosphere by a perfectly reflecting layer at a fixed height, supporting a single transmission mode only. Other properties of sky-wave transmission are, however, retained. Since, in general, sky-wave signals are

randomly polarized, the signal power is proportional to the total power density at the receiver. The power density per unit solid angle, $P(\Omega)$, about the aircraft antenna is given in terms of the antenna gain function and the total transmitted power, P_t, by:

$$P(\Omega) = P_t \frac{G(\Omega)}{4\pi} . \tag{B-6}$$

If $G_1(\Omega)$ and $G_2(\Omega)$ are the gains in any two perpendicular directions of polarization, the power gain of interest here is given by

$$G(\Omega) = G_1(\Omega) + G_2(\Omega) . \tag{B-7}$$

Gains are usually determined for polarization in the θ and ϕ directions of a spherical coordinate system about the aircraft.

The direction of the transmission path, with respect to the aircraft, depends on the relative location of aircraft and ground station. A consideration of all possible directions of transmission leads to a probability distribution expressing the likelihood that a given solid angle sector about the aircraft will contain the transmission path. Since this function is not readily obtainable in practice, the probability density is here taken as a constant over a solid angle secton, Ω_s, considered to be useful for transmissions; no communications are assumed to take place in directions outside this sector. The extent of the useful sector is not well defined and therefore will be taken as another parameter of the evaluation factors. Examination of the performance measures as a function of this sector will show the extent to which this lack of precise knowledge influences antenna ratings

Antenna performance measures have so far been discussed largely in terms of the antenna radiation patterns. The antenna impedance is another important function of the antenna. It is directly related to the maximum obtainable efficiency of the matching circuit which transforms the antenna impedance to that of the transmission line connecting the transmitter and antenna Ohmic losses in the transmission line, matching circuit, and the antenna itself, as well as power lost due to incomplete matching, reduce the total available transmitted power, P_t, in Eq. (B-5). Such losses may therefore be included as a constant fractional multiplier of the gain function. From this point, the gain is to be understood to contain this loss factor unless explicitly stated otherwise.

D. THE VOICE INTELLIGIBILITY INDEX

Articulation scores as observed over the liaison system not only provide a readily measurable performance rating for the circuit but they also have a more direct operational significance than the information capacity The articulation score has therefore been proposed here as the basic measure for the comparison of antenna systems. It may be noted that the articulation score is a function of the amount of information received by the listeners. However, the articulation score cannot be taken as a direct measure of the amount of information in the speech wave.[1]

The relationship between signal-to-noise ratio and articulation scores is discussed in Appendix E. Since, for the constant noise which is assumed here, the signal-to-noise ratio is directly proportional to the antenna gain, the latter could be transformed into articulation scores, provided the constant of proportionality were known. The "Voice Intelligibility Index" is then obtained by averaging articulation scores over the useful solid angle sector, Ω_u. In practice, the constant of proportionality between gain and the signal-to-noise ratio is a function of time, since signal-to-noise ratios vary with ionospheric conditions. The position of the gain on the signal-to-noise ratio scale therefore also varies with time. As discussed earlier, these time functions are ignored here and the relative position of gain and signal-to-noise ratio is regarded as a parameter. It will be seen subsequently that the relative rating of antenna systems is not affected by the omission of the time variations. The term, "Voice Intelligibility Index," was chosen in order to make clear the distinction between this measure and true articulation scores which do depend on the changes of signal and noise.

For the sake of simplicity, a linear approximation to the relation between articulation score and signal-to-noise ratio is used here. This is illustrated in Fig. B-1 where $\mathcal{g}$ denotes the gain function in decibels, i.e.

$$\mathcal{g} = 10 \log_{10} G(\Omega) . \qquad \text{(B-8)}$$

The position of the point $\mathcal{Y}$ on the $\mathcal{g}$ scale is a parameter, as just explained.

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[1] George A. Miller, *Language and Communication*, McGraw Hill Book Co., Inc.; 1951.

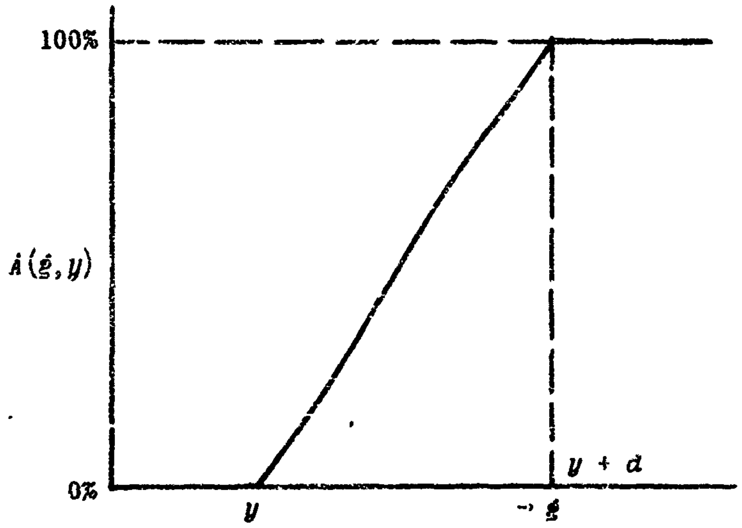

FIG. B-1

ARTICULATION SCORE AS A FUNCTION OF ANTENNA GAIN

The level, y, will be referred to as the threshold level. The range, d, in gain between 0% and 100% articulation can be obtained from the curve of Fig. E-3, from where it is seen to be about 15 db for the tests discussed there. Let $A(g, y)$ be the equation of the curve illustrated in Fig. B-1. The voice intelligibility index, $I(y)$, is then given by the following integral:

$$I(y) = \frac{1}{\Omega_s} \int_{\Omega_s} A(g, y) d\Omega, \tag{B-9}$$

where $A(g, y)$ is given symbolically by

$$\begin{aligned} A(g,y) &= 0 & & g<y \\ A(g,y) &= 100\,\frac{g - y}{d} & & y<g<y + d \\ A(g,y) &= 100 & & g>y \end{aligned} \tag{B-10}$$

as seen from Fig. B-1.

The voice intelligibility index in the form of Eq. (B-9) may be regarded as an average of the function $A(\mathcal{g},y)$ over the solid angle sector, Ω_s. If $p(\mathcal{g})d\mathcal{g}$ is the fraction of all values of $\mathcal{g}$ occurring in Ω_s for which the gain, $\mathcal{g}_1$, lies between the following limits:

$$\mathcal{g} < \mathcal{g}_1 < \mathcal{g} + d\mathcal{g} \ ,$$

the voice intelligibility index may be written in the equivalent form

$$I(y) = \int_{-\infty}^{+\infty} A(\mathcal{g},y)p(\mathcal{g})d\mathcal{g} \qquad \text{(B-11)}$$

which is an average over the gain, instead of an average over the solid angle. Substituting for $A(\mathcal{g},y)$ in Eq. (B-11), it is found that after some reductions,

$$I(y) = \frac{100}{d}\int_{y}^{y+d} \overline{\Phi}(\mathcal{g}>u)du \qquad \text{(B-12)}$$

where $\overline{\Phi}(\mathcal{g}>u)$ is the fraction of all values of $\mathcal{g}$ within Ω_s, which exceed u decibels, i.e.

$$\overline{\Phi}(\mathcal{g}>u) = \int_{u}^{\infty} p(x)dx \qquad \text{(B-13)}$$

If the linear approximation of Eq. (B-10) is used in the formula for average articulation score given by Eq. (E-5), the voice intelligibility index and the average articulation score are seen to differ only in the definition of the distribution function. Average articulation scores were used as an experimental measure of antenna performance during actual flight tests. The two measures differ, since average articulation scores obtained during flight tests include the time variations of the sky-wave signal and those of the noise.

One essential difference between the voice intelligibility index and the performance measure based on average information capacity is the way in which changes in transmitted power affect the ratings. For the voice intelligibility index the loss in power due to ohmic losses anywhere in

the system can be taken account of through a shift of the function $I(y)$, in the direction of the g-axis, by an amount equal to the power transfer efficiency expressed in decibels. The index can therefore be calculated on the basis of the radiation patterns alone. The loss in power through the system is later included in the rating by a simple shift in origin of the g-coordinate.

It was shown earlier that the average information capacity of the liaison system is closely related to the average signal-to-noise ratio, provided these ratios are not too widely scattered from their mean. This condition was shown to be satisfied by aircraft antenna radiation patterns in the high-frequency range. It will now be shown that a similar relationship exists between the voice intelligibility index and the average signal-to-noise ratio. For this purpose, the useful angular sector is divided into three regions:

$$\Omega_1 \text{ over which } g < y$$

$$\Omega_2 \text{ over which } y < g < y + d$$

$$\Omega_3 \text{ over which } g > y + d$$

corresponding to the three ranges over which the function $A(g,y)$ of Eq. (B-10) is continuous and where, of course,

$$\Omega_1 + \Omega_2 + \Omega_3 = \Omega_s$$

If the average gain is taken over the sector Ω_2 rather than over the entire useful sector, the voice intelligibility index is found from Eq. (B-9) to be given, approximately, by

$$I(y) = 100\frac{\Omega_3}{\Omega_s} + \frac{100}{d}\,\frac{\Omega_2}{\Omega_s}\left[10 \log_{10}\bar{G} - y\right] - \frac{217}{d}\,\frac{\Omega_2}{\Omega_s}\,\frac{\overline{G^2} - \bar{G}^2}{\bar{G}^2}. \qquad \text{(B-14)}$$

The last term of this equation has already been shown to be small for h-f aircraft antenna radiation patterns. If it is further assumed that the noise is such that almost the entire pattern within the useful solid sector lies within the range $y < g < y + d$, i.e.

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$$\frac{\Omega_1 + \Omega_3}{\Omega_s} << 1 \qquad \text{so that} \qquad \frac{\Omega_2}{\Omega_s} \approx 1$$

then the voice intelligibility index is given by the following approximate expression

$$I(y) \cong \frac{100}{d} (\bar{g} - y) \tag{B-15}$$

where

$$\bar{g} = 10 \log_{10} \left\{ \frac{1}{\Omega_s} \int_{\Omega_s} G(\Omega) d\Omega \right\}. \tag{B-16}$$

To this degree of approximation, the voice intelligibility index is seen to be a linear function of the threshold level, y, independent of the radiation pattern. Differences in pattern merely change the position of this function, with respect to the g-coordinate, in the same manner as do changes in the power transfer efficiency. An analysis of a large number of radiation patterns to be described presently will show that these approximations are essentially justified.

Let us now examine the effect of fading on the voice intelligibility index. The variations with time of the signal-to-noise ratio may be thought of as variations of the threshold level, y. These values of y are distributed with a density, $p(y)$, which is approximately stationary if suitable time intervals are considered. The average articulation score, $\bar{A}$, is then given in terms of the voice intelligibility index by

$$\bar{A} = \int_{-\infty}^{+\infty} p(y) I(y) dy \,. \tag{B-17}$$

The average articulation score is the evaluation criterion which was measured for various h-f antenna systems during actual flight tests. These are described in Appendix E. Using the approximate expression of Eq.(B-15) for the voice intelligibility index, the average articulation score is found to be given by

$$\bar{A} = \frac{100}{d} (\bar{g} - \bar{y}) \tag{B-18}$$

where $\bar{y}$ is the expected or mean value of the variations in threshold level. This level depends, of course, on the mean signal power as well as on the noise. The main interest of Eq. (B-18) lies in the fact that $\bar{y}$ is a constant, practically independent of the particular aircraft antenna used for transmitting. In a rating of antennas on a relative basis, $\bar{y}$ will cancel out and an evaluation based on the voice intelligibility index can be compared directly with the results obtained from flight tests, in terms of average articulation scores.

E THE RADIATION PATTERN DISTRIBUTION FUNCTION

The radiation pattern distribution function given by Eq. (B-13) has itself been used as a measure of antenna performance.[1] It has been found useful where the noise level is fixed and known in relation to the power density of the signal at the receiver location. In that case, only a single value of the distribution function is obtained which is given by the fraction of the useful solid angle over which the gain function exceeds some fixed minimum level. In our case, however, the entire distribution function is required, for which the minimum level may take on all values between $-\infty$ and $+\infty$. It is easily shown that Eq. (B-13) is identical to the following average over the unit step function:

$$\bar{\Omega}(g > y) = \frac{1}{\Omega_s} \int_{\Omega_s} u(g - y) d\Omega \qquad \text{(B-19)}$$

which is a form more convenient for computational purposes. Here again, changes in power transfer efficiency can be accounted for by a simple translation in origin of the g-coordinate.

F. THE ANTENNA SYSTEM EFFICIENCY

The antenna system efficiency[2] is defined as the fraction of the total power radiated in useful directions. In terms of the gain function,

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[1] A. Ellis, Study of External Navigation Antennas on Lockheed Constellation Aircraft, Report No. 726-IT, August 1949, Airborne Instruments Laboratory.

[2] J. V. N. Granger, "Systems Considerations in Aircraft Antenna Design," Transactions of the I.R.E., PGAE-1; December 1951.

$G(\Omega)$, the antenna system efficiency is given by the integral

$$\eta_s = \frac{1}{4\pi}\int_{\Omega_s} G(\Omega)d\Omega \qquad \text{(B-20)}$$

It should be remembered that the gain is defined here in terms of the total available power. If the usual gain function defined in terms of the total radiated power is used instead, the resulting expression is known as the radiation pattern efficiency, η_p. Letting η_{tr} be the ratio between total radiated power and total available power, the antenna system efficiency will be given by

$$\eta_s = \eta_{tr}\eta_p \qquad \text{(B-21)}$$

The approximate expression of Eq. (B-15) shows the following relationship between voice intelligibility index and antenna system efficiency:

$$I(y) = \frac{100}{d}\left\{K + 10\ \log_{10}\eta_s - y\right\} \ . \qquad \text{(B-22)}$$

where K is a constant. A similar expression is obtained from Eq. (B-18) for the average articulation score.

To the degree of this approximation, the voice intelligibility index and the logarithm of the antenna system efficiency are linearly related. The close relationship between articulation scores and voice intelligibility index makes it possible, then, to interpret differences in antenna system efficiency in terms of articulation scores — the parameter most significant to the system as a whole. This will be more fully investigated in the next section. The antenna system efficiency is the simplest of the performance measures from a practical point-of-view and it has therefore been chosen as the measure of antenna performance in the specification.

G RELATIVE PERFORMANCE OF ANTENNA SYSTEMS

As stated earlier, antenna ratings must be relative, since the performance of the system as a whole depends on a large number of other factors. The quantity of interest is the relative standing of several

proposed antennas which might be used for h-f transmissions from a given aircraft, the performance of one of the antennas being chosen as a reference

Consider first a comparison of antennas based on the voice intelligibility index. It will be shown presently that the linear approximation of Eq. (B-22) is valid over a considerable range of values of y. Let the comparison be made at the same noise level, y_a. Denoting quantities for the two antennas under comparison by subscripts 1 and 2, one finds for the difference in voice intelligibility index:

$$I_2 - I_1 = \frac{100}{d}\left\{10 \log_{10}\frac{\eta_{s2}}{\eta_{s1}}\right\} \qquad \text{(B-23)}$$

It should now be recalled that in deriving the voice intelligibility index all time variations in signal-to-noise ratio were neglected. When fading is taken into consideration, it will be found that the range in signal-to-noise ratio between 0% articulation and 100% articulation is, in general, considerably larger than the range, d, obtained for tests using white noise and a steady signal. The difference in voice intelligibility index as given by Eq. (B-23) therefore differs by some factor from a true difference of articulation scores, and this proportionate factor depends on the time variations of the ionosphere.

If, under otherwise identical conditions, two antenna systems are found to have equal voice intelligibility indices, average articulation scores over the two systems would be observed as identical also. This is evident by inspection of Eq. (B-17). Consider, therefore, changes in the variable y as being due to changes in available transmitted power, and examine Eq. (B-22) for the conditions under which equal voice intelligibility indices are obtained. It is then found that

$$y_2 - y_1 = 10 \log_{10}\frac{\eta_{s2}}{\eta_{z2}} \qquad \text{(B-24)}$$

where $(y_2 - y_1)$ is the increase (in decibels) in available power required in the system using antenna No. 1, over that of antenna No. 2, so that the average articulation score is the same over both systems. This measure of the relative performance of the antennas is independent of

ionospheric time variations. The power change required to obtain equal system performance can be visualized in terms of size, weight, and cost of the transmitting equipment, and, as just shown, it is simply related to the ratio of the antenna system efficiencies. Finally, the term "equal system performance" as used here is synonymous with "equal articulation score, on the average." A comparison of antennas on this basis therefore seems most suitable for the present application. The required change in power for equal system performance can be expressed approximately in terms of changes in articulation score, if desired, from the experimentally determined relation between articulation score and median signal-to-noise ratio obtained during the tests described in Appendix E.

It may be noted that the antennas can be rated in terms of power changes required for equal system performance, where system performance now is measured by the radiation pattern distribution function. It will be seen presently, however, that such comparisons depend rather critically on the parameter y. Furthermore, the radiation pattern distribution function lacks the direct operational significance of the average articulation score. This means of rating antennas is therefore not recommended here.

H. RADIATION PATTERN ANALYSIS

Several methods for comparing the performance of h-f antenna systems have just been discussed. It was shown that they are simply related to each other, provided certain assumptions are justified. To show the validity of these assumptions a large number of aircraft antenna radiation patterns were therefore examined, and the performance ratings obtained by the different methods were compared. The useful solid angle sector, on which all these ratings depend, was used as a parameter in the computations. By examining the change in rating of the antennas with changes in useful angular sector it can be determined to what degree of accuracy the extent of this sector has to be known.

No computations were made of the average information capacity. It was felt that this performance measure, while interesting from a theoretical point-of-view, is too lengthy to evaluate for the large number of patterns required in practice. A discussion of the average signal-to-noise ratio is given in Appendix C where detailed account has been taken of many of the ionospheric variables neglected in the rest of the report.

Radiation patterns of antennas for three aircraft were used in the analysis. A complete list of antennas and of the frequencies at which patterns were available is given in Table B-I. All the patterns of antennas on the C-54 aircraft were recorded at the Antenna Laboratory of the Ohio State University Research Foundation.[1,2,3] As noted in the

TABLE B-I

LIST OF ANTENNA RADIATION PATTERNS USED FOR ANALYSIS

AIRCRAFT	TYPE OF ANTENNA	FREQUENCIES (Mc)	SOURCE OF PATTERNS
C-54	Fixed Wire (Open) Tail Cap Single Wing Cap Two Wing Caps out of Phase (← →) Two Wing Caps in Phase (→ →)	4, 6, 6, 9, 14, 19, 25 2, 4, 6, 9, 19, 25 2, 4, 6, 8, 10, 12, 14, 25 2, 4, 6, 8, 19, 25 2, 4, 6, 8, 25	Antenna Laboratory The Ohio State University Research Foundation Columbus, Ohio
Constellation - 749 Constellation - 1049	Fixed-Wire Configurations No. 1, 3, 4, 5* Tail Cap (Outside Fin) Single Wing Cap	3.105, 5.00, 8.900 11.915, 16.320 5.00, 8.90, 11.915, 20.00 5.00, 8.90, 11.915, 20.00	Stanford Research Institute
B-47	Fixed-Wire (Open) Tail Cap Single Wing Cap	2, 3, 7, 10, 16, 24 2, 4, 6, 8, 10, 12, 14, 16, 19, 22, 25 2, 4, 6, 8, 10, 12, 14, 16, 19, 22, 25	Boeing Aircraft Co. Seattle, Washington

* These configurations consist of fixed wires to the three tail fins.

No. 1. In-line, insulated antenna fed; outboard antennas insulated and grounded

No. 3. Right, insulated antenna fed; in-line and left antennas insulated and grounded

No. 4. In-line, shorted antenna fed; outboard antennas insulated and grounded

No. 5. Right, shorted antenna fed; in-line and left antennas shorted and grounded

Note: The terms "grounded" and "open" refer to the forward terminals of the antenna, the terms "shorted" and "insulated" to the tail end.

reports just referred to, some of these radiation patterns are in error. At the time the analysis was undertaken, the Ohio State data constituted the most complete set of radiation pattern data available for several high-frequency antennas on a single aircraft, and these patterns are adequate for the type of analysis to be carried out here. However, the

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1 Electronic Subdivision Wright-Patterson AFB, Patt[illegible]easurements of the Isolated Wing Cap Antennas on the C-54 Airplane, 1 September 1950, Contract No. W33-038-ac-18823.

2 Electronic Subdivision, Wright Patterson AFB, Pattern Measurements of the Isolated Vertical Stabilizer Antenna on a C-54 Airplane Model, 10 November 1950, Contract No. W33-038-ac-18823.

3 Weapons Components Division, Wright-Patterson AFB, Pattern Measurements of the Long Wire Antenna on a C-54 Airplane Model, Contract No. AC-18823

radiation pattern efficiency of antennas on the C-54 aircraft were re-determined, at Stanford Research Institute, for the comparison of flight test results with measurements made on aircraft models.

Radiation patterns of antennas on the Lockheed Constellation aircraft were available from the files of two other research projects[1,2] and are used here with permission of the contractors. The patterns of the flush-mounted antennas were taken on a different type of Constellation aircraft than were the fixed-wire patterns. The data on these aircraft presented below, therefore, should also be taken as a test of the evaluation methods, rather than as quantitative ratings for the actual antennas.

Patterns for the B-47 aircraft were measured at the Boeing Aircraft Company, Seattle, Washington, and were made available for this analysis by courtesy of Boeing personnel.

The starting point of the computations were polar field strength plots taken in the two directions of polarization, for different slices through the actual solid angle radiation patterns. The patterns were measured in the standard manner, on reduced scale models of the aircraft. The pattern data was then transferred to punched cards and all the computations were carried out on IBM equipment.* It should be pointed out that all of the results to be presented are based on the radiation patterns alone. The power transfer efficiencies can be estimated if the impedance of these antennas is known. Inclusion of these efficiencies would alter the quantitative results obtained. However, it would not change the conclusions reached as to the justification of the different approximations discussed in the previous sections.

In Figs. B-2, B-3, and B-4, the voice intelligibility index is plotted as a function of the threshold level at different frequencies. For the sake of clarity, curves for some of the antennas were omitted in

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* The reading out of the pattern data and the subsequent computations were performed by the Telecomputing Corporation, Burbank, California.

[1] A. R. Ellis and C. W. Steele, Pattern Study of Wire Antennas on 749A Constellation Aircraft, Final Report, September 1951, on SRI Project No. 425 for Transworld Airlines, Stanford Research Institute, Stanford, California.

[2] John Taylor, Flush-mounted H-F Antennas for the 1049 Constellation Aircraft, Final Report, 1 February 1952, on SRI Project No. 409 for Lockheed Aircraft Corporation, Stanford Research Institute, Stanford, California.

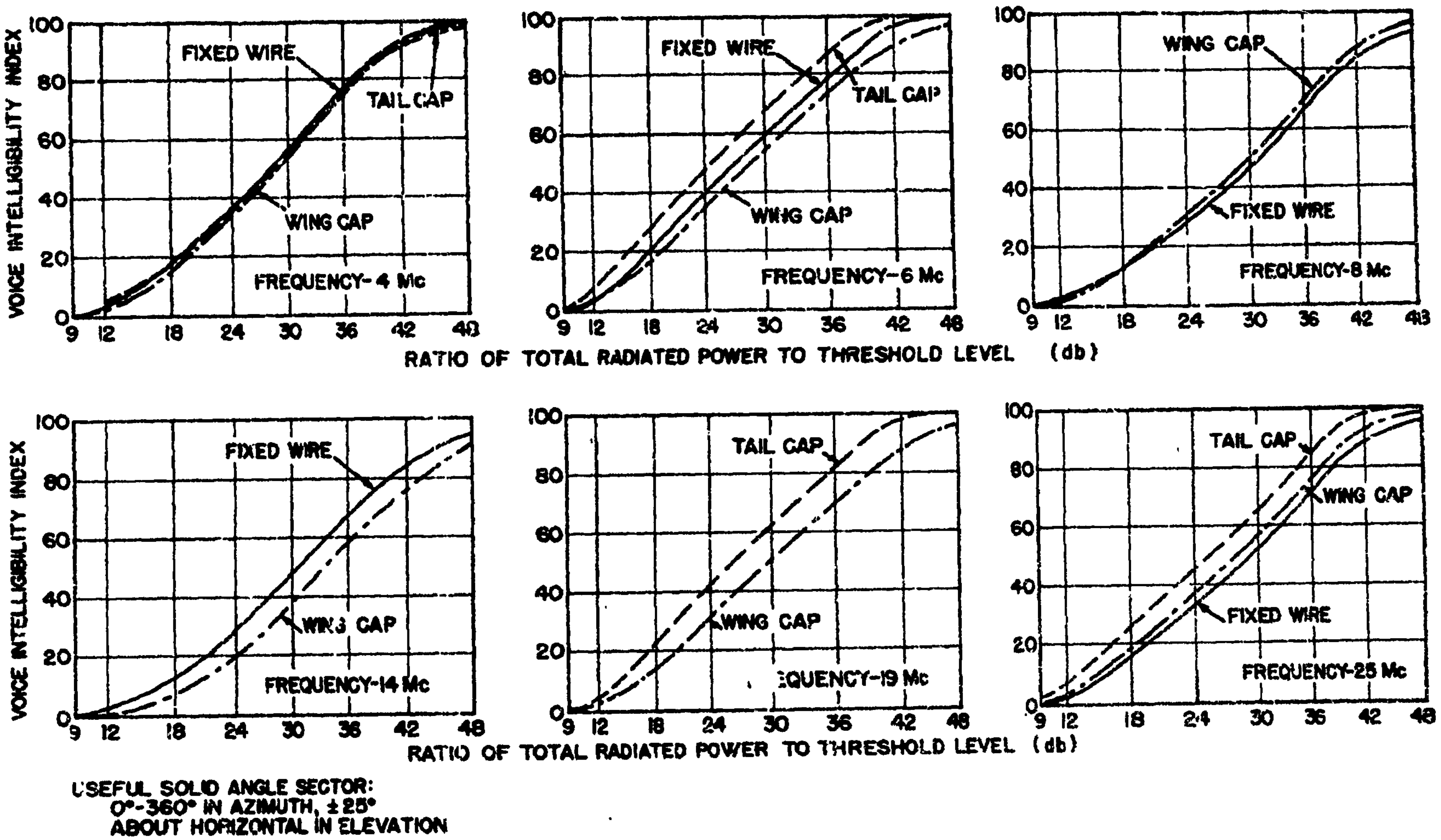


FIG. B-2

VOICE INTELLIGIBILITY INDEX AS A FUNCTION OF THRESHOLD LEVEL FOR ANTENNAS ON C-54 AIRCRAFT

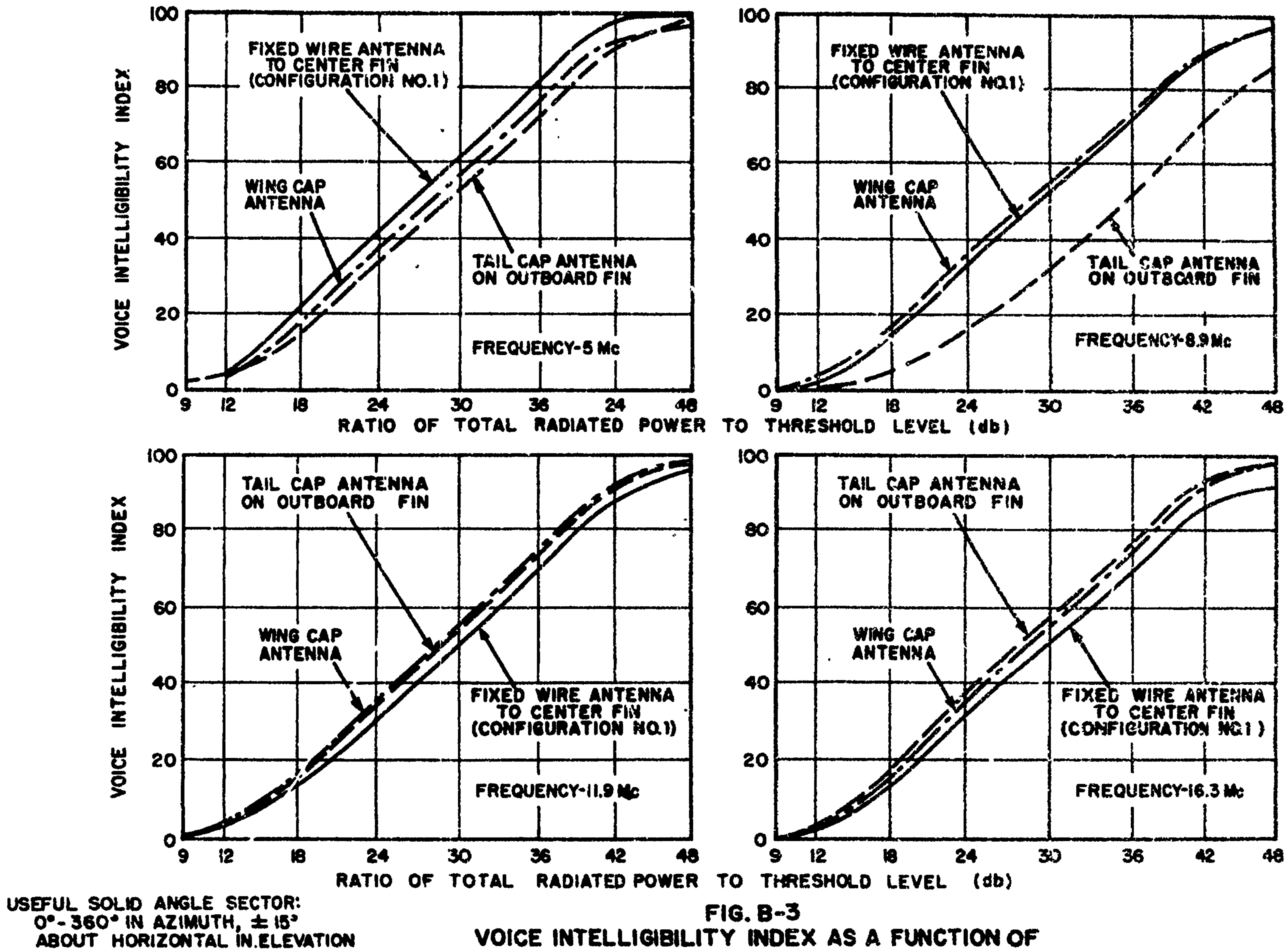


FIG. B-3
VOICE INTELLIGIBILITY INDEX AS A FUNCTION OF
THRESHOLD LEVEL FOR ANTENNAS ON LOCKHEED CONSTELLATION

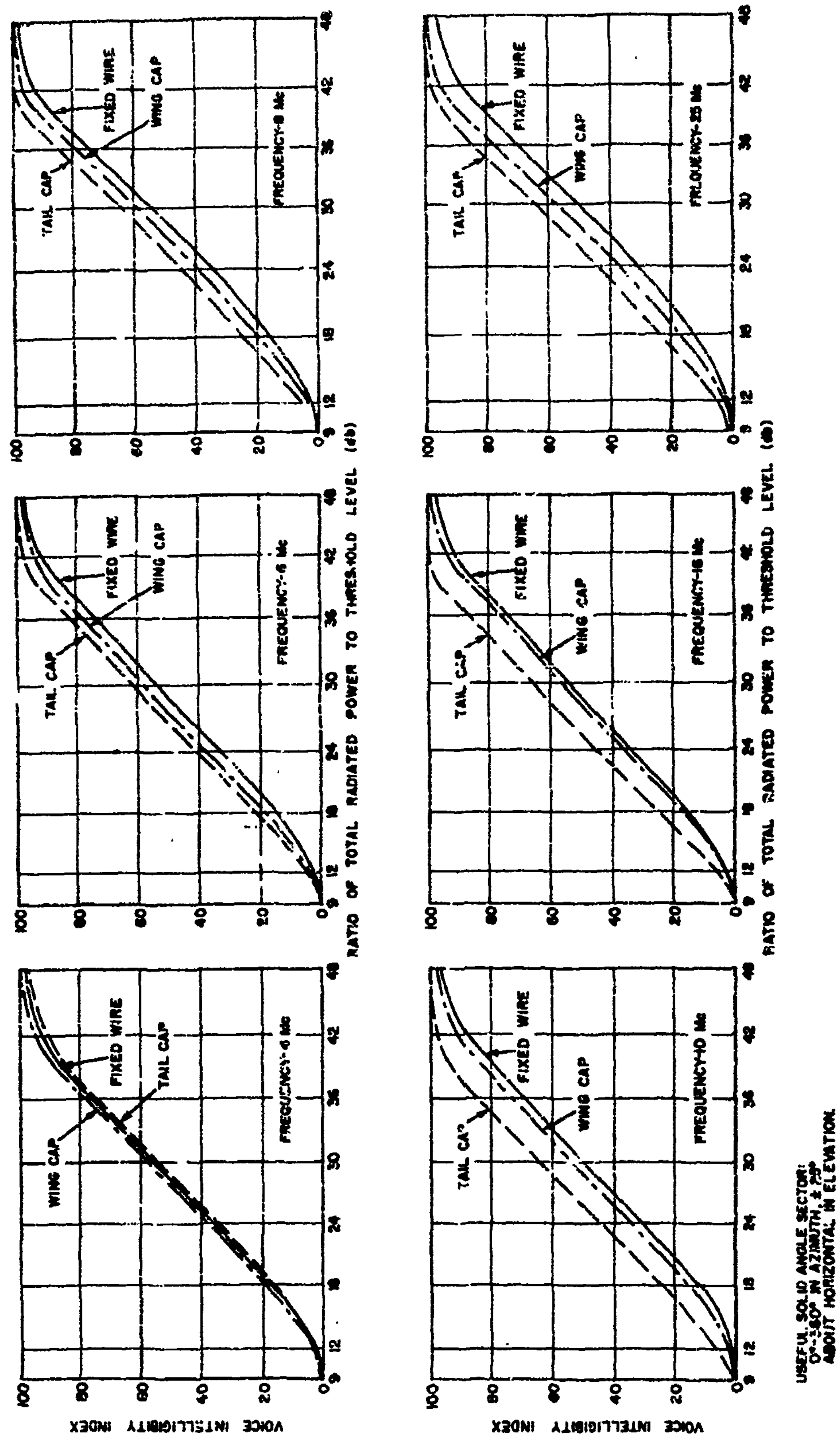


FIG. B-4

VOICE INTELLIGIBILITY INDEX AS A FUNCTION OF THRESHOLD LEVEL FOR ANTENNAS ON B-47 AIRCRAFT

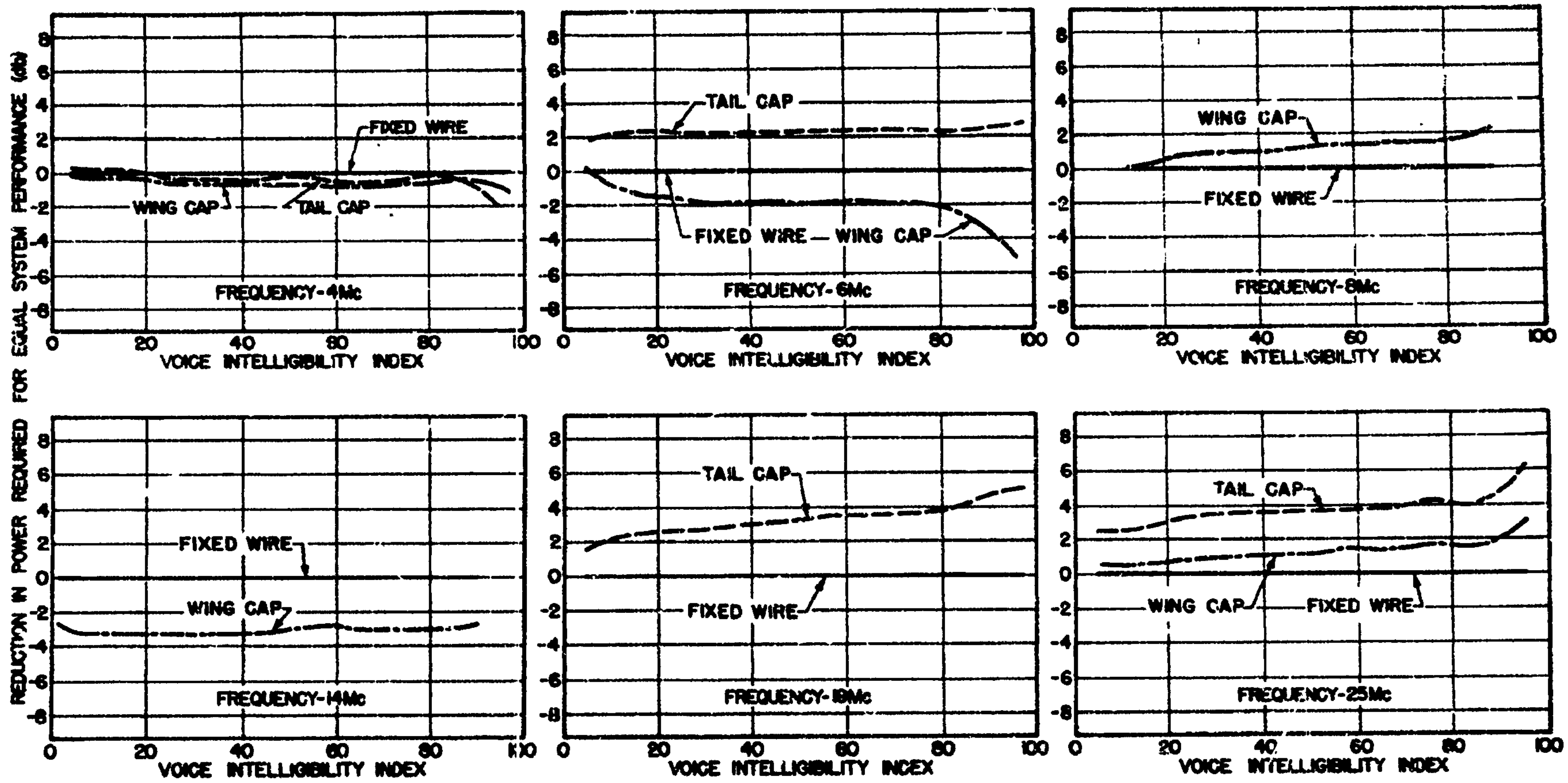
the figures. Since an increasing threshold level corresponds to increasing noise, the actual variable used is the negative of this level, so that increases in the coordinate corresponds to increases in signal-to-noise ratio. The index is seen to be a linear function of the threshold level for a wide range of the variable and for all of the antenna systems illustrated.

The shape of the functions are equal for the different antennas on the same aircraft and at a given frequency. The rating of the antennas in terms of the power changes required for equal system performance is therefore entirely justified. This is illustrated in Fig. B-5 where these power changes for antennas on the C-54 aircraft are given as a function of the voice intelligibility index. The rating of antennas in this fashion is seen to be practically independent of the value of the index at which the comparison is made. The approximations made in deriving Eq. (B-15) are, therefore, seen to be satisfied.

The radiation pattern distribution function for antennas on the C-54 aircraft are shown in Fig. B-6. Power changes required for equal system performance can be obtained from these curves in the same fashion as for the voice intelligibility index, where, of course, the term "system performance" must be understood in this altered sense. Figure B-7 shows such a comparison of antennas, based on the radiation pattern distribution function. This measure of antenna performance is seen to depend quite strongly on the particular value of the function at which the comparison is to be made. Similar results were obtained for the antennas on the other aircraft. This illustrates one of the reasons for rejecting the radiation pattern distribution function as a practical measure of the performance of high-frequency aircraft antennas.

Radiation pattern efficiencies are shown as a function of frequency in Fig. B-8. This is the function of the radiation patterns obtained when carrying out the calculations required by the specification. The trend of these curves is therefore of interest although the meaning of the function is defined only relative to the value obtained for a reference antenna system. The actual measure of antenna performance is the ratio of the radiation pattern efficiency of the antenna under test to that of the fixed-wire reference antenna.

All the evaluation measures have so far been presented for a fixed useful solid angle sector. The next series of figures illustrates the



USEFUL SOLID ANGLE SECTOR:
0°-360° IN AZIMUTH, ± 25°
ABOUT HORIZONTAL IN ELEVATION

FIG. B-5

COMPARISON OF FLUSH-MOUNTED ANTENNAS WITH FIXED-WIRE ANTENNA ON C-54 AIRCRAFT

9-888C-F-380

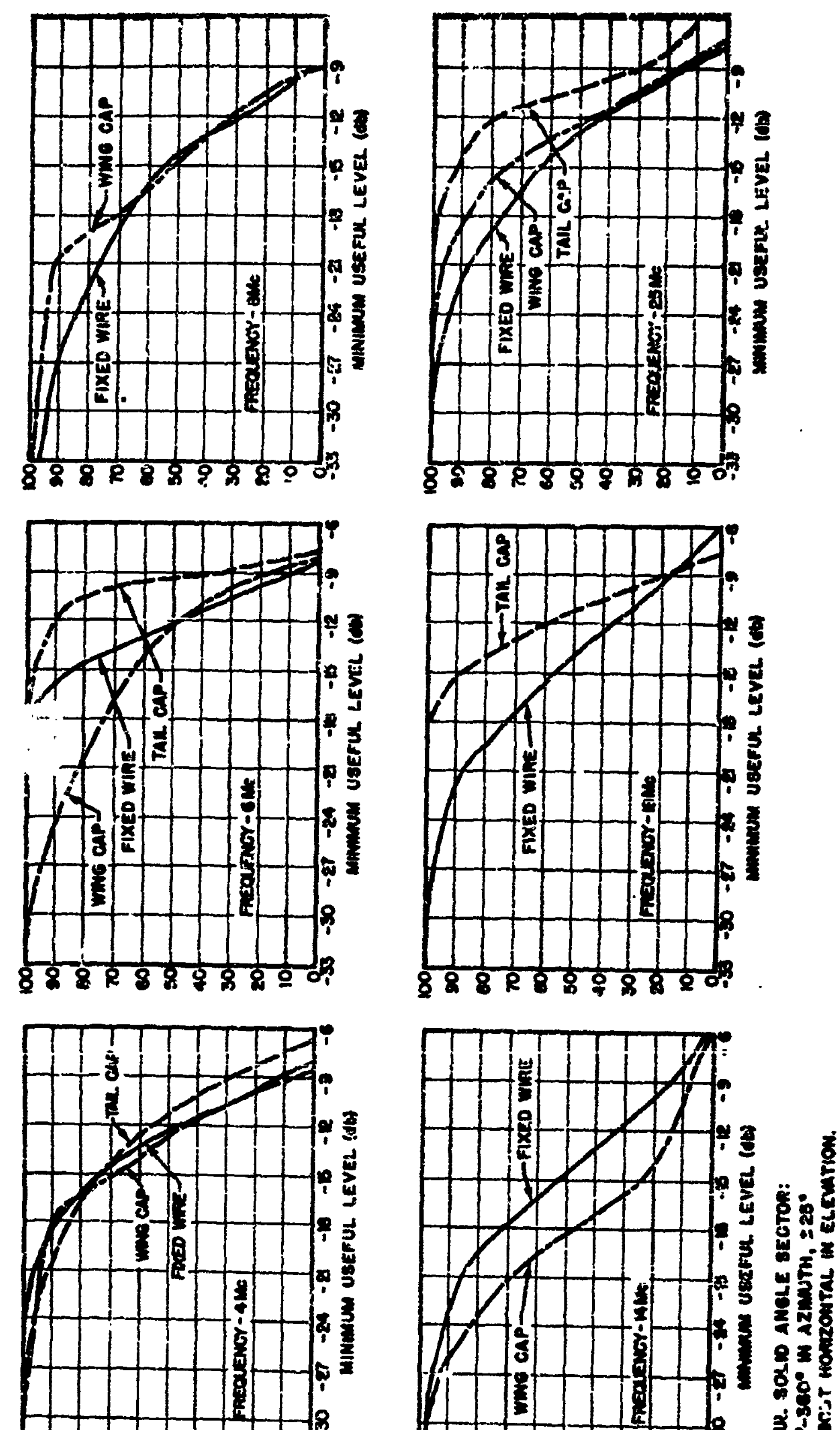


FIG. B-6

RADIATION PATTERN DISTRIBUTION FUNCTION OF ANTENNAS ON C-54 AIRCRAFT

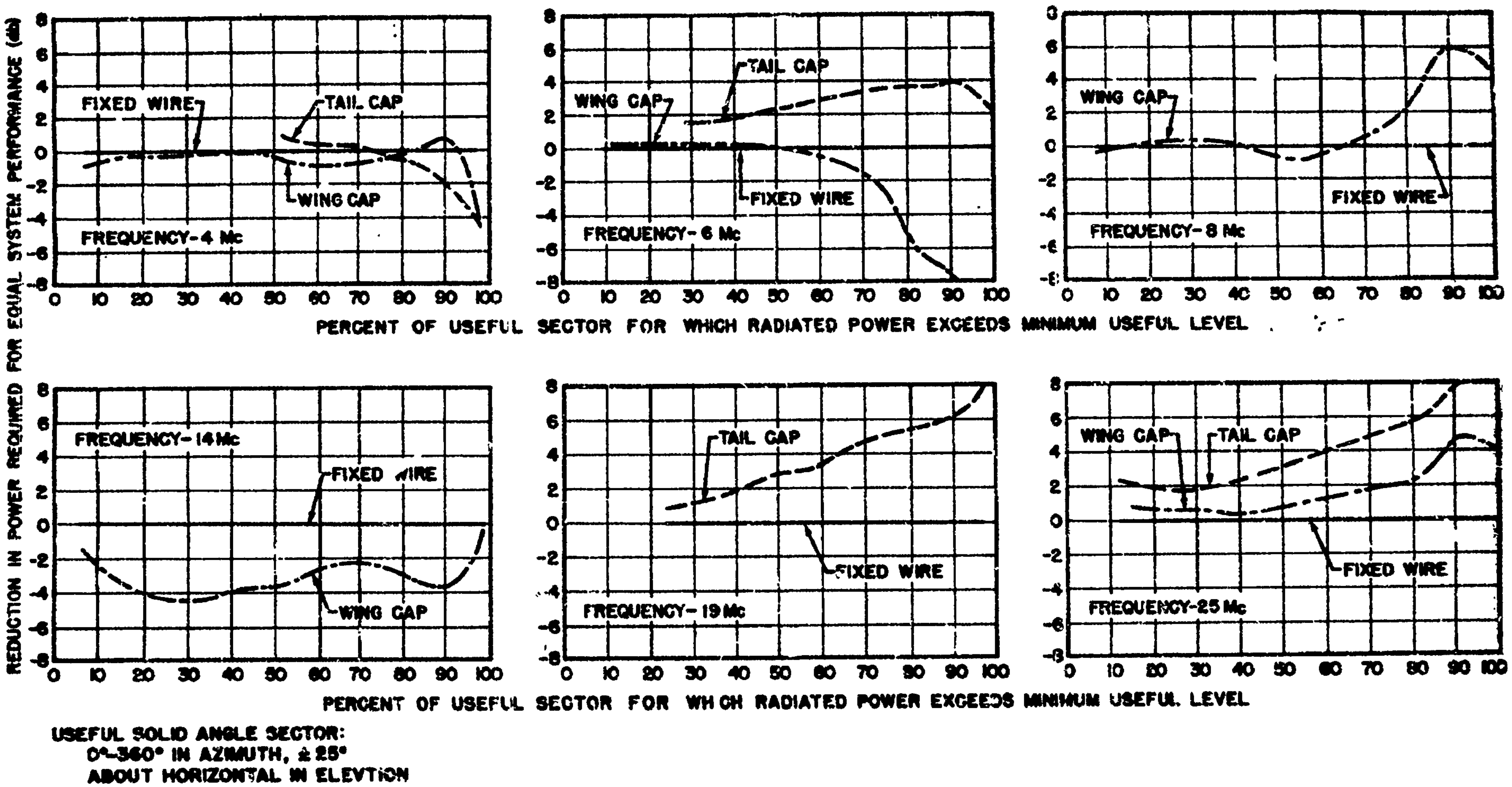


FIG. B-7

COMPARISON OF FLUSH-MOUNTED ANTENNAS WITH FIXED-WIRE ANTENNA ON C-54 AIRCRAFT, ON THE BASIS OF THE RADIATION PATTERN DISTRIBUTION FUNCTION

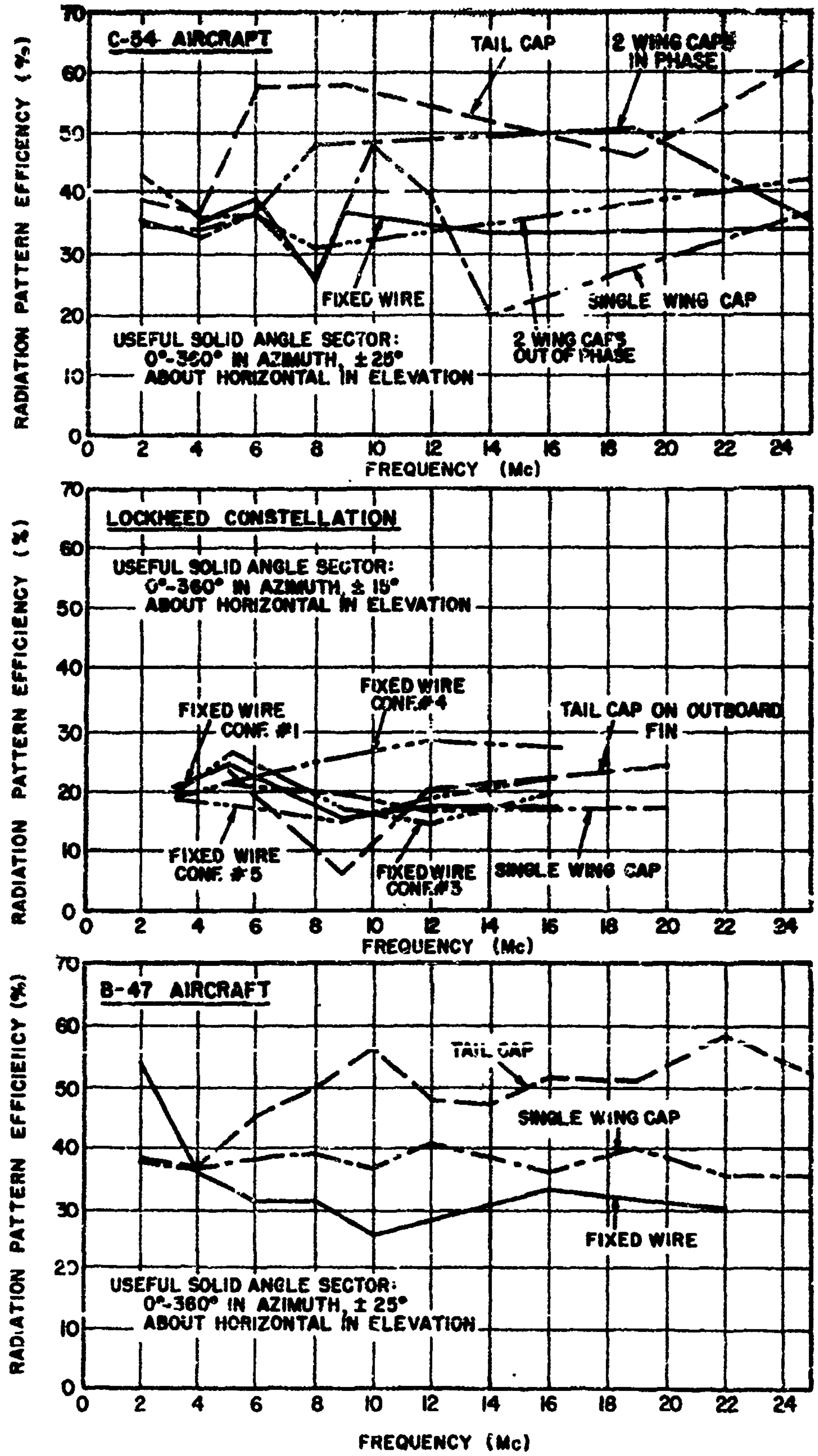


FIG. B-8
RADIATION PATTERN EFFICIENCY
AS A FUNCTION OF FREQUENCY

C-60SC-F-262

changes in antenna rating caused by changes in the sector considered useful for transmissions from the aircraft. The independent variable of these curves is the useful solid angle expressed as a percentage of all solid angles about the aircraft. In terms of this scale, the useful solid angle sector of ±30 degrees about the horizontal corresponds to the 50% point of the abscissa. It should be noted that changes in the useful sector are assumed to be due to changes in the vertical sector. All useful directions considered include azimuthal angles about the aircraft from 0 degrees to 360 degrees. The ratings on which these curves are based were obtained from the ratios of the radiation pattern efficiencies, in the manner just outlined. Figure B-9 shows the change in ratings as a function of the useful solid sector, at various frequencies, for antennas on the C-54 aircraft. Figures B-10 and B-11 give similar plots for the antenna systems on the Lockheed Constellation and on the B-47 aircraft, respectively. It is seen that the rating of antennas does depend to some extent on the vertical sector over which the pattern is to be averaged, and this dependence increases with increasing frequency. In all cases illustrated, however, a decrease of the sector considered useful from 50 degrees to one of about 20 degrees will hardly alter the rank order of the different antennas on a given aircraft, and will cause only small changes in the actual measure used to express antenna performance. To the degree of approximation illustrated, the exact distribution of vertical angles of transmission need not be known, and the use of the fixed useful vertical sector of ±30 degrees required in the specification is fully justified in practice.

The last figures show the equivalence of performance ratings based on the voice intelligibility index and those based on the radiation pattern efficiency. Ratings for the antennas on the C-54 aircraft, the Lockheed Constellation, and the B-47 aircraft are shown as a function of frequency in Figs. B-12, B-13, and B-14 respectively. For practical purposes, the ratings obtained by the use of the two different measures can be considered identical. For this reason, the radiation pattern efficiency can be used in the manner described in the report with the assurance that antenna evaluations based on it can be interpreted in terms of average articulation scores.

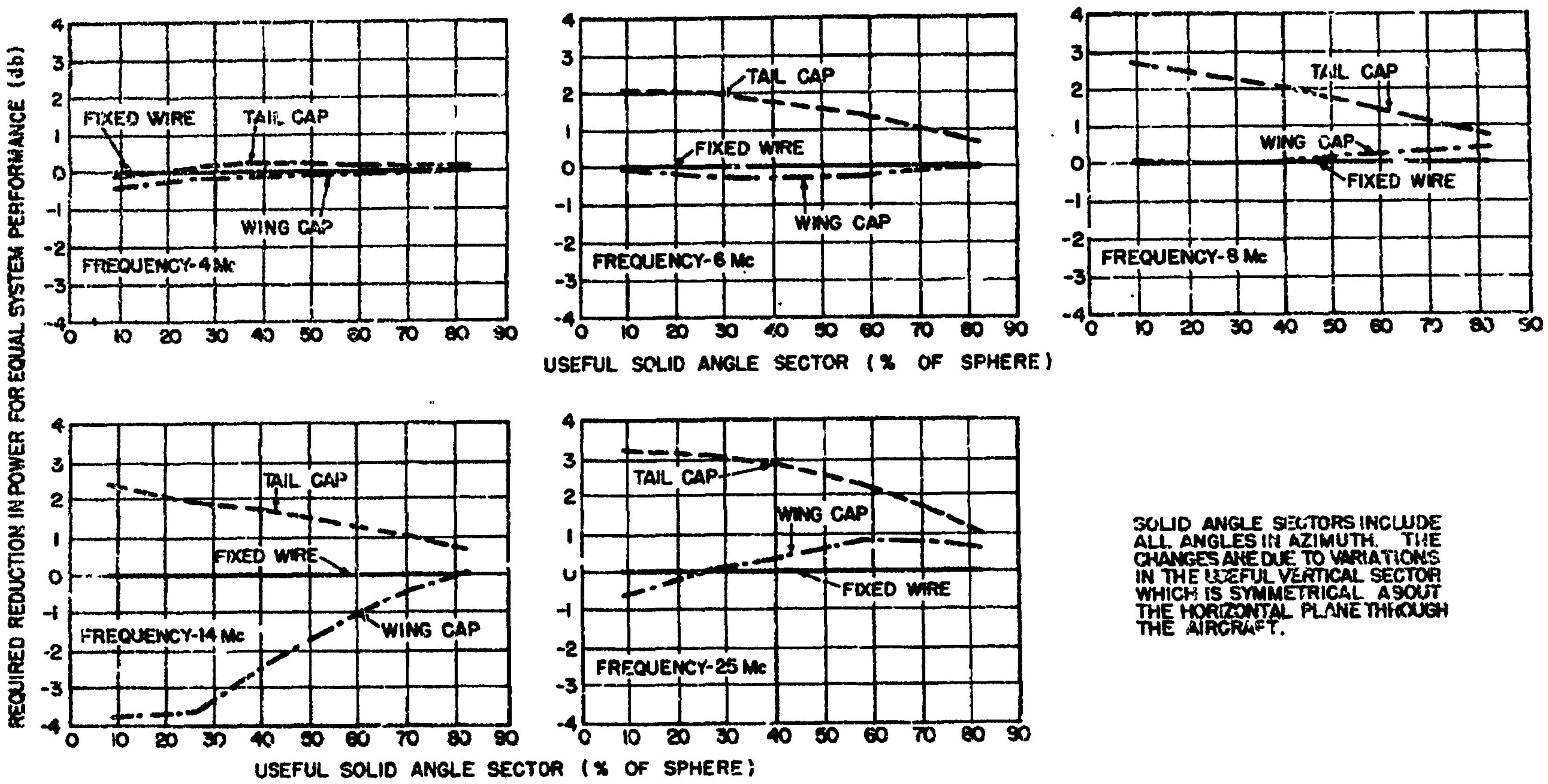
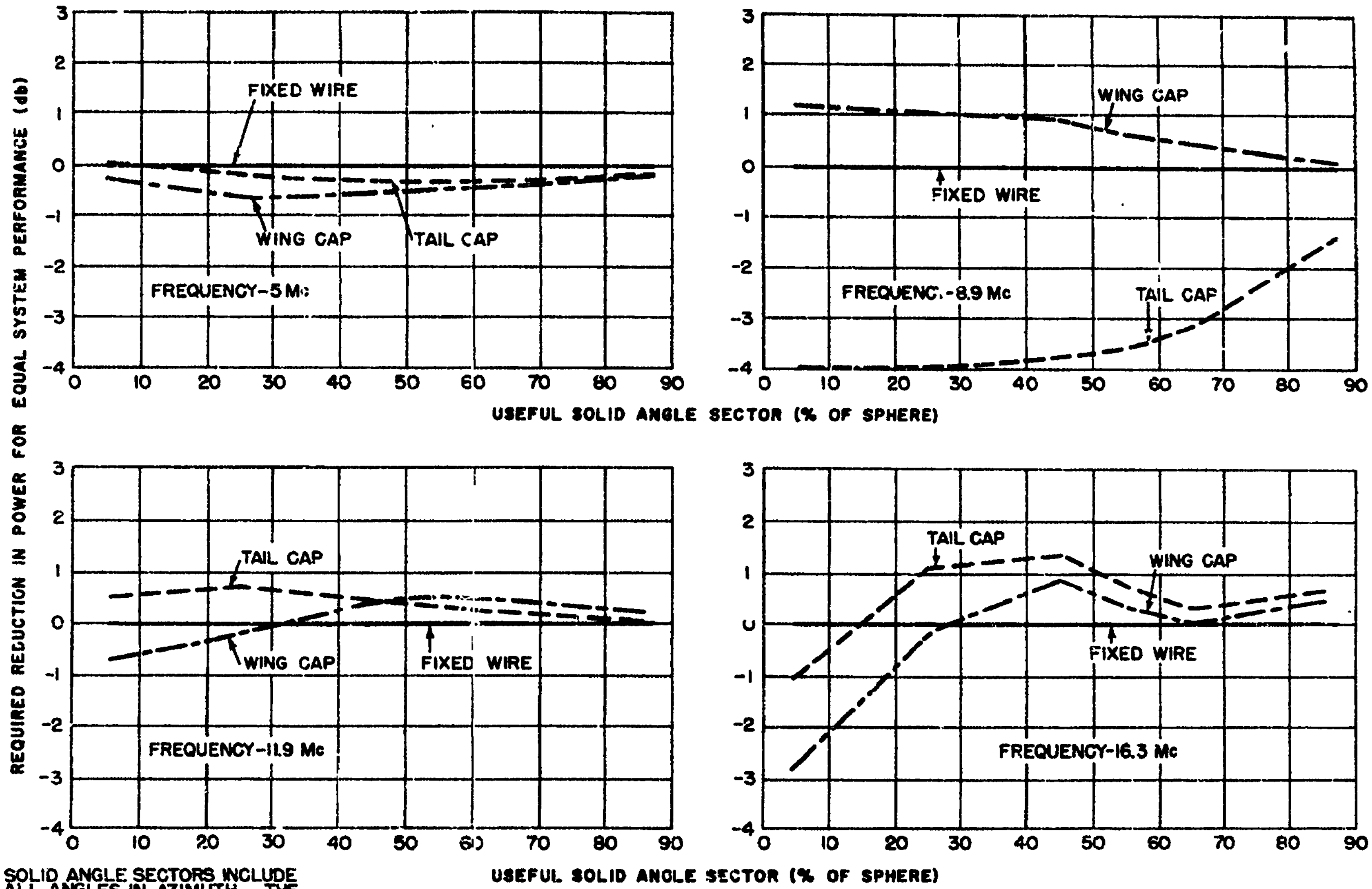


FIG. B-9

PERFORMANCE OF ANTENNAS ON C-54 AIRCRAFT, AS A FUNCTION OF USEFUL SOLID ANGLE SECTOR

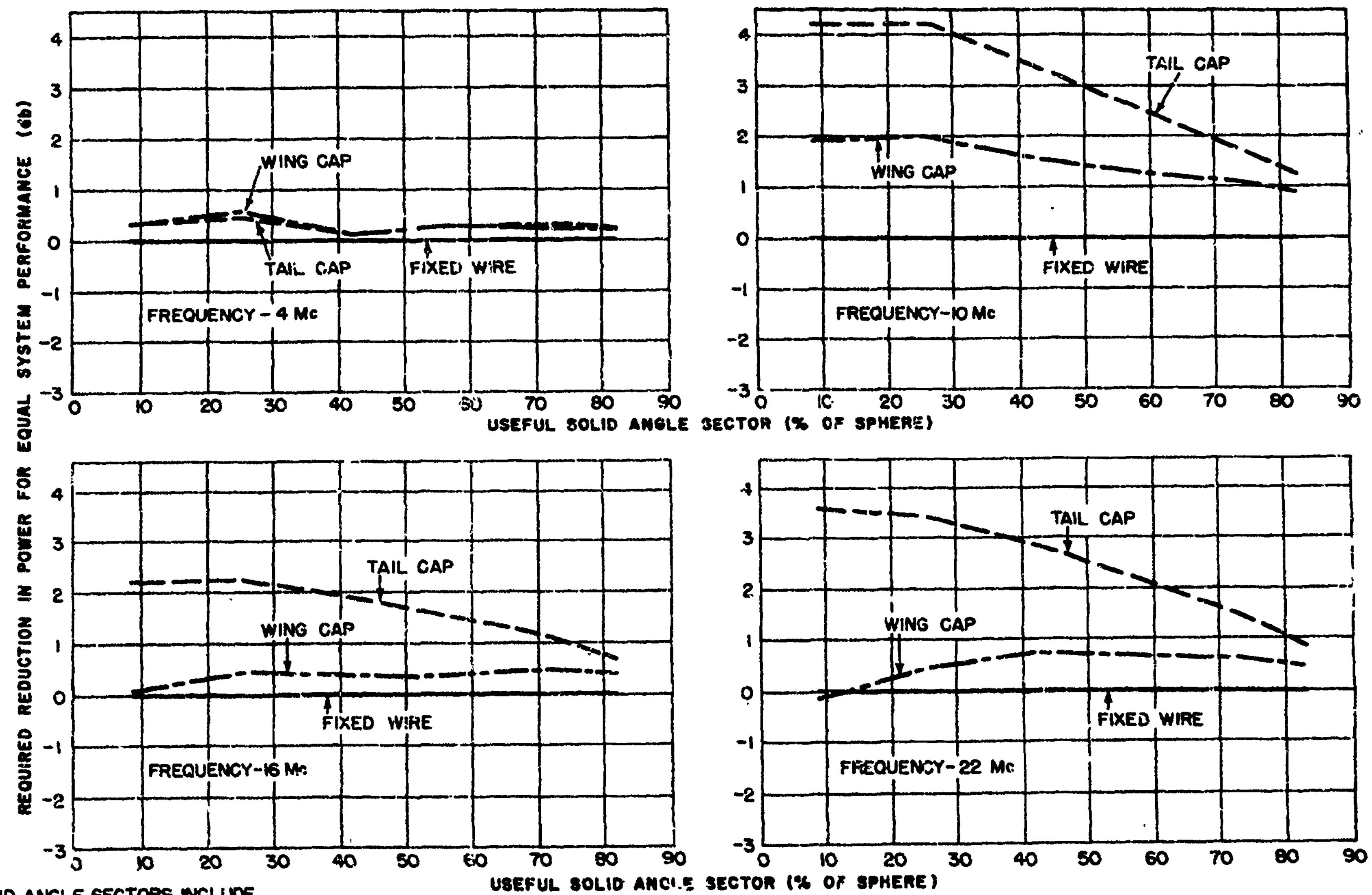


SOLID ANGLE SECTORS INCLUDE ALL ANGLES IN AZIMUTH. THE CHANGES ARE DUE TO VARIATIONS IN THE USEFUL VERTICAL SECTOR WHICH IS SYMMETRICAL ABOUT THE HORIZONTAL PLANE THROUGH THE AIRCRAFT.

FIG. B-10

PERFORMANCE OF ANTENNAS ON LOCKHEED CONSTELLATION, AS A FUNCTION OF USEFUL SOLID ANGLE SECTOR

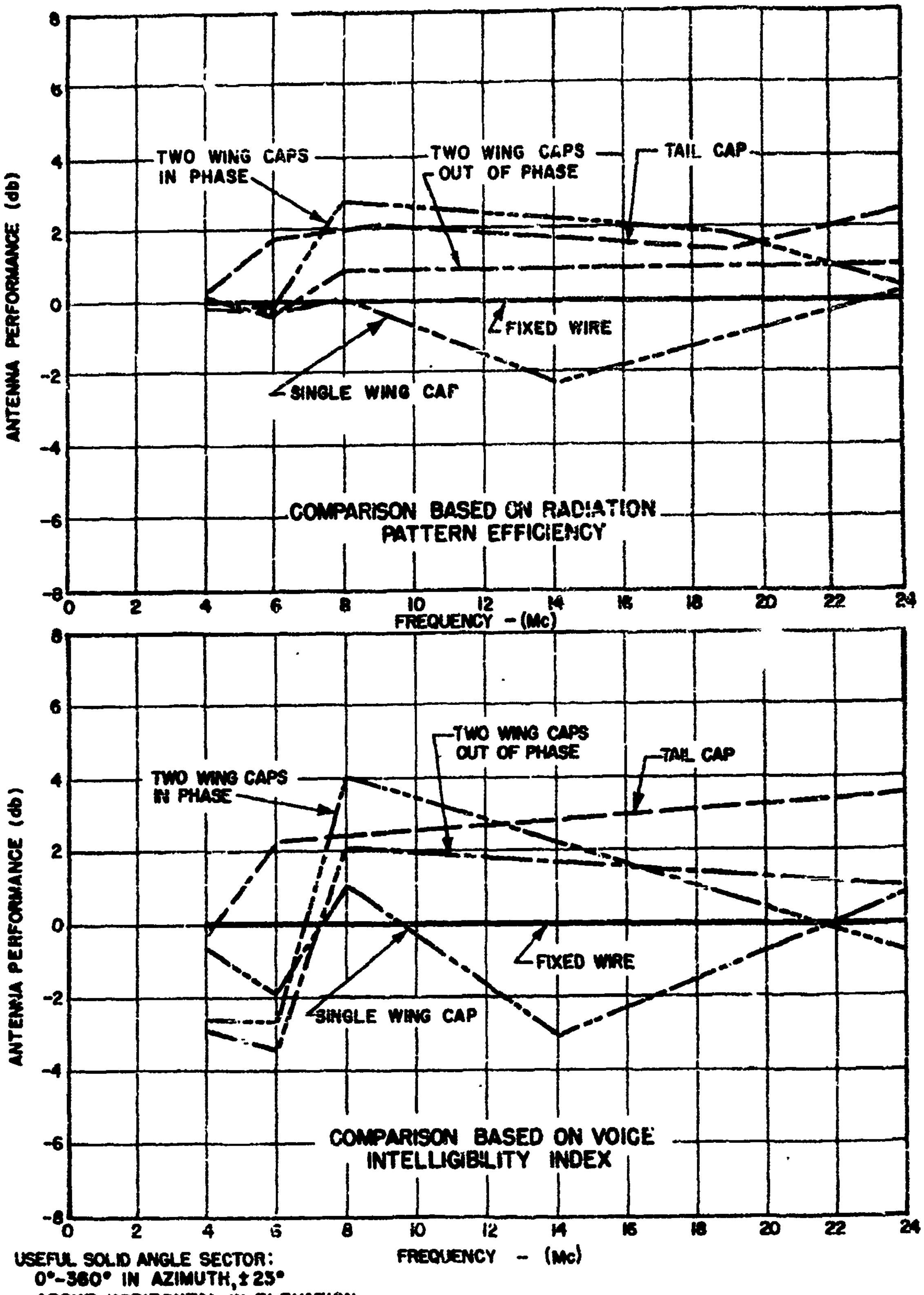
C-600C-F-264



SOLID ANGLE SECTORS INCLUDE ALL ANGLES IN AZIMUTH. THE CHANGES ARE DUE TO VARIATIONS IN THE USEFUL VERTICAL SECTOR WHICH IS SYMMETRICAL ABOUT THE HORIZONTAL PLANE THROUGH THE AIRCRAFT.

FIG. B-11

PERFORMANCE OF ANTENNAS ON B-47 AIRCRAFT, AS A FUNCTION OF USEFUL SOLID ANGLE SECTOR



USEFUL SOLID ANGLE SECTOR:
0°-360° IN AZIMUTH, ±23°
ABOUT HORIZONTAL IN ELEVATION

FIG. B-12

PERFORMANCE RATINGS OF ANTENNAS
ON C-54 AIRCRAFT

B-808C-F-266

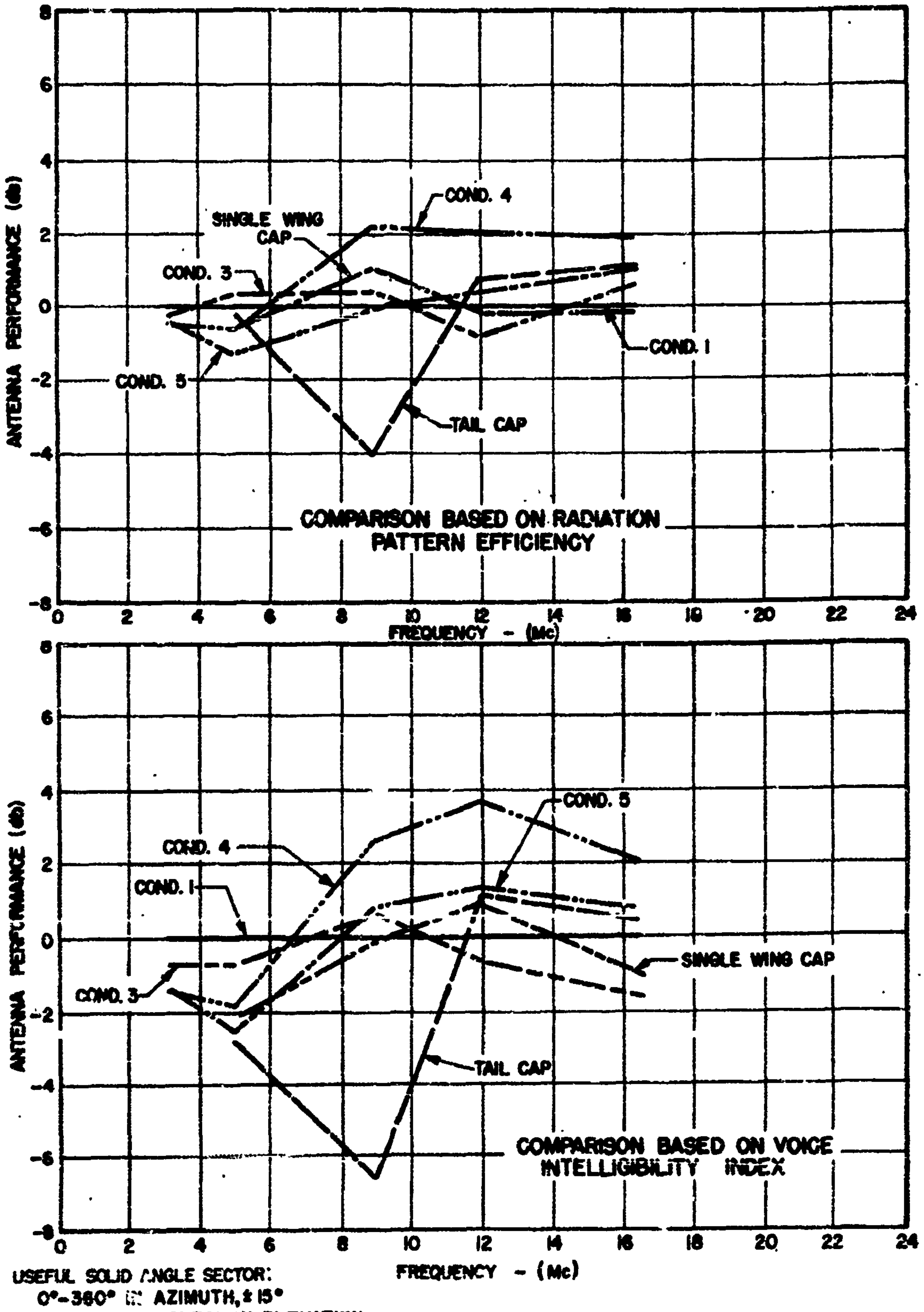
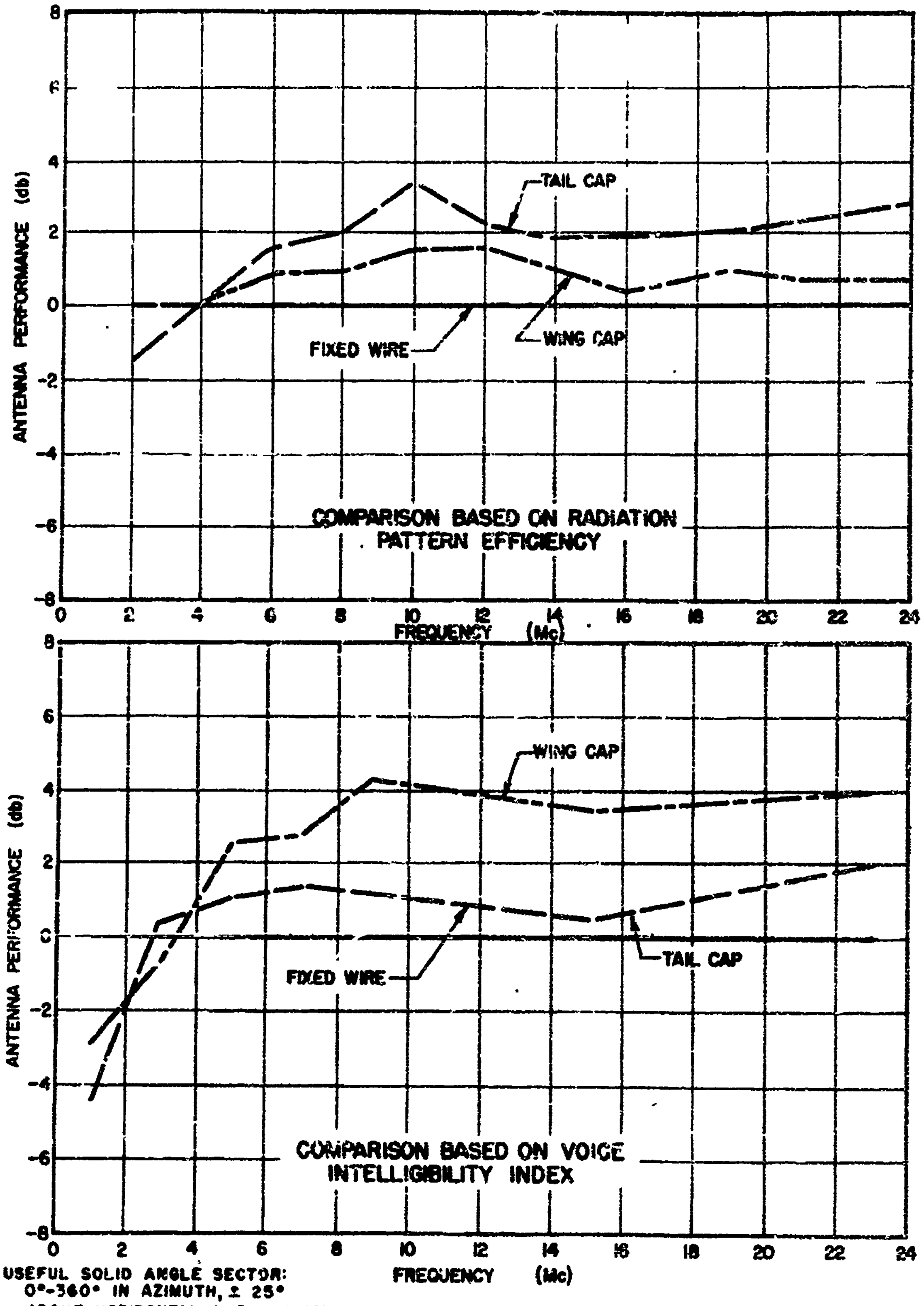


FIG. B-13

PERFORMANCE RATINGS OF ANTENNAS
ON LOCKHEED CONSTELLATION

B-60SC-F-257



USEFUL SOLID ANGLE SECTOR:
0°-360° IN AZIMUTH, ± 25°
ABOUT HORIZONTAL IN ELEVATION

FIG. B-14

PERFORMANCE RATINGS OF ANTENNAS
ON B-47 AIRCRAFT

B-SOSC-F-288

APPENDIX C

THE INFLUENCE OF THE IONOSPHERE ON THE PERFORMANCE RATING OF H-F AIRCRAFT ANTENNAS[1]

A. INTRODUCTION

In this appendix, a "factor of merit" for h-f aircraft antennas is described which takes more detailed account of the effects of the ionosphere on the system than the methods discussed elsewhere in this report. Instead of a useful solid angle sector about the antenna, the probability distributions of radio contacts with angular directions are retained. The effects of the ionosphere are also expressed in terms of probability distributions which lead to further averaging over such variables as time of transmissions, geographical location of the transmission path, and operating frequency of transmission.

Factors of merit were computed for three h-f antenna systems on a C-54 aircraft. The answers to these computations did not differ greatly from those derived by the much simpler procedures recommended elsewhere in this report. Since extensive labor is required to obtain numerical results, such detailed considerations do not seem warranted in practice, at least not for the case of the system discussed here. The method is of interest nevertheless, inasmuch as it shows the scope of the approximations made in obtaining a more practical performance measure. The detailed procedure to be described may also be useful for performance evaluation of h-f circuits where the number of possible situations is more limited than in the system under discussion.

It is shown in Appendix D that transmission from an aircraft to the ground is of more importance in aircraft antenna evaluation than reception on the aircraft. The rating scheme will therefore be discussed for the transmitting case.

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[1] E. J. Moore, "Factor of Merit for Aircraft Antenna Systems for the Frequency Range from 3 to 30 Mc"; Transactions of the I.R.E., Professional Group on Antennas and Propagation, August 1952.

B. THE AVERAGE SIGNAL-TO-NOISE RATIO FOR A SPECULAR IONOSPHERE

The factor of merit is defined as the average signal-to-noise ratio observed at ground-based receivers when transmissions take place from the aircraft. This average must take into consideration all the conditions under which the system may operate, such as the various possible relative locations of the transmitter and receiver; the different ionospheric conditions which may prevail during such transmissions; the various frequencies which may be used; the differing atmospheric noise conditions at different times of the day; and different geographical locations of the transmission path. Let ζ stand for the aggregate of variables affecting the signal-to-noise ratio, $S(\zeta)/N(\zeta)$, at ground-based receiving sites. As already indicated, these variables are the antenna radiation patterns, the transmitted power, and atmospheric noise; as well as time, geographical location of the transmission path, frequency, distance of transmission, and orientation of the transmission path with respect to the aircraft. A probability density function, $p(\zeta)$, describes the likelihood of occurrence of the situation, ζ. These probabilities must be based on the total life span of the particular type of aircraft for which an antenna is to be designed. If one type of aircraft is to be used in greatly different kinds of services, the suitability of the antenna system must be determined separately for each type of service. The factor of merit, μ, is then given by the average signal-to-noise ratio

$$\mu = \int p(\zeta) \frac{S(\zeta)}{N(\zeta)} d\zeta \ , \qquad \text{(C-1)}$$

the integration being carried out over all values of the variables ζ.*

For the present, a perfectly reflecting, non-attenuating ionospheric layer at a fixed height, H, will be assumed. As before, the actual transmitting antenna on the aircraft is replaced by an equivalent antenna on the ground, the gain of which combines the gains in the two planes of polarization of both the direct sky wave and the wave arriving at the ionosphere after a ground reflection.

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* The relation between the factor of merit and other measures of system performance is discussed in Appendix B.

The gain, $G_t(\theta,\phi)$, of this equivalent antenna is thus given by:

$$G_t(\theta,\phi) = G'_\theta(\theta,\phi) + G'_\phi(\theta,\phi) + [r_\theta^2(\theta)G'_\theta(\pi - \theta,\phi) + r_\phi^2 G'_\phi(\pi - \theta,\phi)]. \quad \text{(C-2)}$$

Primes indicate the actual gains of the aircraft antenna in a spherical coordinate system about the aircraft, while r_θ and r_ϕ are the magnitudes of the ground reflection coefficients for the two directions of polarization.

Figure C-1 illustrates the case of an n-hop sky-wave path between the equivalent transmitting antenna at T and a receiver at R. The angle subtended by the transmission path at the center of the earth is denoted by ψ,

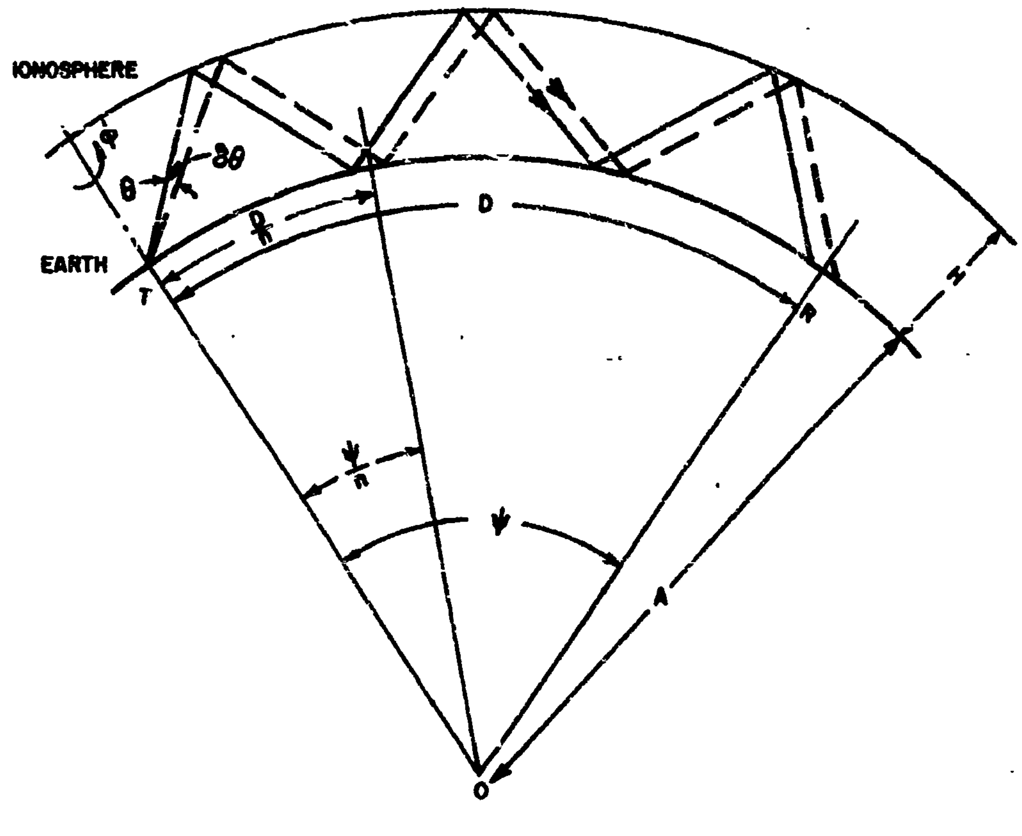

FIG. C-1
GEOMETRIC RAY PATH FOR N-HOP SKY-WAVE TRANSMISSION

so that ψ/n is the angular distance subtended by a single hop. At a fixed frequency, and considering transmission paths of n hops only, Eq. (C-1) reduces to the surface integral

$$\mu = A^2 \int p(\psi,\theta) \frac{S_o(\psi,\theta)}{N_o} \sin \psi d\psi d\phi . \tag{C-3}$$

The subscripts on S and N refer to the fact that power absorption in the ionosphere is, at present, not being considered. The radius of the earth is denoted by A. Atmospheric noise is, of course, independent of the coordinates of the aircraft, but varies with the time of day, and with the geographical location of the receiver. These variations will be considered later. The integration is carried out over all angles, ϕ, in azimuth about the aircraft, and over a range of angular distances, ψ, extending from zero out to the limit of possible n-hop transmission. It should be noted again, that the coordinates ψ and ϕ give the location of the ground station with respect to the aircraft. The angle of transmission, θ, and the angular distance of transmission, ψ, are functionally related by an expression involving the height, H, of the ionosphere and the number, n, of hops. It is easily shown that

$$\tan \theta = \frac{\left(1 + \frac{H}{A}\right) \sin \frac{\psi}{2n}}{\left(1 + \frac{H}{A}\right) \cos \frac{\psi}{2n} - 1} . \tag{C-4}$$

The height of the ionosphere is always much smaller than the radius of the earth. This leads to the simpler approximate expression

$$\cot \theta = \cot \frac{\psi}{2n} - \tan \frac{\psi}{4n} . \tag{C-5}$$

The received signal power, $S_o(\psi,\phi)$, must now be expressed in terms of the gain function of the transmitter and receiver. Let $P_t(\theta,\phi)$ be the power per unit solid angle radiated in the indicated direction. In terms of the gain

$$P_t(\theta,\phi) = \eta_{tr} \frac{P_t}{4\pi} G_t(\theta,\phi) , \tag{C-6}$$

where P_t is the total available transmitter power, η_{tr} is the fraction of that power radiated into space, and the gain is defined by Eq. (C-2).

Following Bremmer,[1] consider an elementary pencil of rays leaving the transmitter at the angle θ, and having an angular spread of $d\theta$ and $d\phi$ in the directions of these two coordinates, respectively. The total power transported by this group of rays is

$$\eta_{tr} P_t(\theta,\phi) \sin\theta d\theta d\phi . \qquad \text{(C-7)}$$

Referring again to Fig. C-1, the area of cross section of the pencil of rays at the receiver, R, is given by

$$A^2 \sin\psi \cos\theta d\psi d\phi . \qquad \text{(C-8)}$$

The total power flow must still be that given in Eq. (C-7) since unattenuated propagation was assumed. The total power per unit area normal to the rays is therefore

$$\frac{\eta_{tr} P_t(\theta,\phi) \sin\theta}{A^2 \sin\psi \cos\theta} \frac{d\theta}{d\psi} .$$

If A_r is the absorptive cross section of the receiving antenna, the received signal power is obtained as

$$S_o(\psi,\phi) = \frac{\eta_{tr} P_t}{4\pi} A_r G_t(\theta,\phi) \frac{\tan\theta}{A^2 \sin\psi} \frac{d\theta}{d\psi} . \qquad \text{(C-9)}$$

The factor, $\tan\theta$, leads to a theoretically infinite power density for the tangent rays. This is due to focusing by the concave, mirror-like ionospheric layer assumed here. In practice, this increase of power over that predicted from the length of the transmission path alone will be smaller because of ionospheric perturbations. Furthermore, ground losses and shadowing effects will prevent radiation and reception at angles less than about 3 degrees above the horizontal plane through the ground station.

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[1] H. Bremmer, *Terrestrial Radio Waves*, p. 169; Elsevier Publishing Co., New York; 1949.

It has been stated, however, that the focusing of rays near the horizon is the main factor responsible for long distance transmission with little power.[1]

A signal may arrive at the ground station from any azimuthal direction, and at angles of elevation depending upon the distance between the aircraft and the ground-based receiver. The ground antenna must be able to receive signals arriving from aircraft at all headings about the ground station. An omni-directional pattern in azimuth is therefore assumed here for the antennas of the ground installations. If, in addition, the frequency of transmission is close to the muf for the path, the vertical angle of arrival of signal and noise will be approximately the same. Under these conditions the factor of merit is independent of the receiving cross section, A_r, and it is given by

$$\mu = \frac{\eta_{tr} P_t}{4\pi} \int_0^{\pi/2} \int_0^{2\pi} p\,\psi,\phi \; \frac{G_t(\theta,\phi)}{N_o} \tan\theta d\theta d\phi \qquad \text{(C-10)}$$

where N_o is a factor proportional to the atmospheric noise power density at the ground station.

The function, $p(\psi,\phi)$, must be determined from operational considerations such as those described in Chapter 2 of this report. Taking the aircraft as a fixed reference point, $A^2 p(\psi\ \phi)\sin\psi d\psi d\phi$ expresses the probability that a receiving station is located within the element $A^2 \sin\psi d\psi d\theta$ of the earth's surface. The probability density will usually be obtained as the product, $p(\psi)p(\phi)$, where $p(\phi)$ is the probability density of radio contacts with respect to azimuthal angles about the aircraft, and $p(\psi)$ is the probability density of radio contacts with respect to distance between the aircraft and a ground station. In order to carry out the integrations of Eq. (C-10) $p(\psi)$ must be expressed in terms of θ by means of Eq. (C-4) or Eq. (C-5). This transformation depends on ionospheric conditions, since it involves the effective height of the ionospheric layers as well as the number of hops of the sky-wave signal.

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[1] Karl Rawer, "Calcul du Champ de l'Onde d'Espace"; La Revue Scientifique, Vol. 85, pp. 361-369; April 1947.

C. AVERAGE SIGNAL-TO-NOISE RATIO AND ACTUAL IONOSPHERE

The concept of a specular ionosphere, which has been used so far, must now be amended to take account of such properties of sky-wave transmission as the maximum usable frequency above which transmission over a given path becomes impossible; attenuation of the waves in traversing the ionosphere; transmissions by different modes, i.e. via different ionospheric layers and with different number of hops; and variations in atmospheric noise.

The absorption considered here is of the nondeviative type.[1] It takes place in the lower regions of the ionosphere, in the *D*-layer and lower part of the *E*-layer. The fact that both of these layers disappear at night leads to enormous changes in received signal power with the time of day. Absorption is also dependent on the season of the year and the period of the sunspot cycle, the geographical location of the transmission path, and the ionospheric layer by means of which propagation takes place. Finally, absorption decreases rapidly with increasing frequency of transmission. The received power, S, can be written in terms of the unabsorbed power, $S_{\bullet}$, considered previously, and an absorption index, α, as

$$S = S_{\bullet} 10^{-2\alpha} . \tag{C-11}$$

The muf is dependent on the same factors as the absorption index. It is always preferable to operate near the muf, for several reasons. As just stated, absorption decreases very rapidly as the frequency is increased. Atmospheric noise is, of course, also less attenuated at the higher frequencies, which makes the signal-to-noise ratio much more constant with frequency than the signal alone. On the other hand, the noise power from the individual lightning flashes which cause atmospheric noise is approximately inversely proportional to the square of the radio frequency. The signal-to-noise ratio therefore increases with increasing frequency. Another advantage of operating near the muf is the fact that under these conditions the skip zone is as large as possible. All radio frequency sources which might produce interference, located closer to the receiver than the transmitting station, are thereby effectively eliminated. This fact is of special importance at night when ionospheric absorption is negligibly small.

[1] National Bureau of Standards, Ionospheric Radio Propagation, Circular 462, Chapter 7; June 25, 1948

In practice, the number of available frequencies is limited. Furthermore, the muf for a given path is not known with certainty, in advance. Let f_k be one of the assigned frequencies of transmission, and let f_m be the muf under given circumstances as predicted from available data. There is a probability, $p(f_k|f_m)$, that the frequency, f_k, will be used for this transmission. As discussed in Chapter 2, usual operating practice corresponds to a probability of unity for use of the frequency closest to but less than the optimum traffic frequency. The latter is taken as 85% of the predicted muf for the $F2$-layer, and is equal to the predicted E-layer muf.

Three ionospheric layers support sky-wave transmissions — the E-layer at a virtual height of about 110 km, the $F1$-layer at a height of about 200 km, and the $F2$-layer at an average height of 320 km. The $F2$-layer is the most important one for transmissions over distances greater than about 2000 km.[1] The comparison of aircraft antennas discussed here is based largely on transmissions over distances beyond this range, so that E-layer and $F1$-layer propagation can be neglected.

The height of the $F2$-layer also varies with time, frequency, distance of transmission, and geographical location of the transmission path. The relation between distance of transmission and vertical angle of transmission given by Eqs. (C-4) or (C-5) depends on this height and therefore on the various ionospheric conditions over which the factor of merit is to be averaged. Here, by assuming the $F2$-layer as fixed at an average height of 320 km, this difficulty is avoided. Such an assumption represents an error of less than 5 degrees in vertical angle of transmission, for distances of transmission less than 1800 km

The factor of merit, as given by Eq. (C-10), must now be averaged over all possible ionospheric conditions under which aircraft-to-ground communications are to take place. Let $p(t)dt$ be the relative frequency with which communications take place during the time interval, dt. This can be separated out into probability densities of radio contacts with time of the day, month of the year, and period of the sunspot cycle. Similarly, the geographical location of the mid-point of the path is characterized by the coordinate, g, which occurs in the interval, dg, with a probability, $p(g)dg$. Averaging over all these variables, the factor of merit is obtained as

[1] K. Rawer, "Ausbreitungsvorhersage für Kurzwellen mit Hilfe von Ionosphärenbeobachtungen," Archiv der Elektrischen Uebertragung, Vol. 5, p. 154; 1951.

$$\mu = \frac{P_t}{4\pi} \sum_k \eta_{tr} f_k \int_t \int_g \int_0^{\pi/2} \int_0^{2\pi} p[f_k | f_m(t,g,\psi)] \; p(t)p(g)p(\psi)p(\phi)$$

$$G_t(\theta,\phi,f_k) \frac{10^{-2a(t,g,f_k,\psi)}}{N(t,g,f_k)} \tan\theta \; d\phi d\theta dg dt \; . \qquad \text{(C-12)}$$

The variables on which the different quantities in this equation depend have been indicated explicitly. It should be noted again that for the single ionospheric layer of fixed height assumed here, the variables, ψ, and, θ, are related through Eq. (C-5). Only one mode consisting of the minimum possible number of $F2$-layer hops is assumed to exist at any one time.

The factor of merit can be written in the form

$$\mu = \frac{P_t}{4\pi} \sum_k \eta_{tr} f_k \int_0^{\pi/2} \int_0^{2\pi} G(\theta,\phi,f_k) \; w(\theta,\phi,f_k) \; \tan\theta \; d\phi d\theta \qquad \text{(C-13)}$$

where

$$w(\theta,\phi,f_k) = p(\phi) \; p[\psi(\theta)] \int_t \int_g p(f_k | f_m) \; p(g)p(t) \; \frac{10^{-2a}}{N} \; dg dt \; . \qquad \text{(C-14)}$$

The integrand of Eq. (C-13) is a product of two terms: the antenna radiation pattern in the form of the gain function, and a weighting function, $w(\theta,\phi,f_k)$. The latter contains all factors depending on the ionosphere, as well as the various probability density functions expressing operational factors of the system.

D. THE FACTOR OF MERIT FOR ANTENNAS ON A C-54 AIRCRAFT

Practical application of the factor of merit presents considerable difficulties. Focusing of the tangent rays resulting in the tan θ-factor of the integral was already mentioned. Except for the papers by Rawer, referred to earlier, very little attention has been paid to this effect. No data is available to show the actual observed magnitude of the increase of field strength with increasing angle from the vertical. In the computations described below, tan θ was arbitrarily replaced by sin θ.

The computations of the ratio $10^{-2a}/N$ were based on data published by the Central Radio Propagation Laboratory.[1] The reliability of the atmospheric noise data and the data giving absorption indices has not been fully evaluated. Atmospheric noise arising from distant sources disappears completely at frequencies between 12 and 25 Mc. The dominant noise then is due to either thunder storms in the vicinity of the receiver, cosmic noise, or interference from other stations operating near the frequency used for transmission. The noise level at which the latter sources take the place of the atmospheric noise (given by the published curves) is another unknown variable. In the present computations, an arbitrary, fixed minimum noise level relative to the atmospheric noise curves was assumed.

Another assumption open to question is the neglect of all *E*-layer and *F*1-layer modes. Some attempt was made to estimate the importance of the sporadic *E*-layer, especially for nighttime transmissions. Here again, the available data is too scant for any but the roughest computations. The effect of sporadic *E* proved to be unimportant, at least insofar as it could be estimated by available methods. The postulate of only one active transmission mode at any one time is also open to question.

The properties of the earth's surface along the transmission path enter the factor in two ways. The radiation pattern of the equivalent transmitter on the ground, as given by Eq. (C-2), depends on the ground reflection coefficient in the vicinity of the aircraft. An average value was chosen for this coefficient in order to avoid further weighted averaging over various ground conditions. For multi-hop propagation, there are additional ground losses at the different ground reflection points; these were neglected entirely.

The weighting function was computed for the following conditions: ionospheric reflection points were taken to be located with equal probabilities at 20 degrees north latitude in the eastern zone, 40 degrees north latitude in the western zone, and 58 degrees north latitude in the intermediate zone.[*] Maximum usable frequencies were obtained at four-hour intervals throughout the day, for the months of August 1951 and January 1952,

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[1] National Bureau of Standards, <u>Ionospheric Radio Propagation</u>, Circular 462, Chap. 7; June 25, 1948.

[*] These zones refer to the three world regions for which separate *F*2-layer muf prediction charts are prepared.

using the Central Radio Propagation Laboratory predictions.[1] These two months occurred at about the half-way point of the decreasing part of the sunspot cycle. Equal use of the radio system during summer and winter was assumed. Distances of transmission ranged from 1200 km to 3600 km, using the one-hop *F2*-mode, and from 3600 km to 5600 km, via the two-hop *F2* mode.

Two different combinations of probabilities of radio contacts with time and distance were considered. In the first, radio contacts were taken as being uniformly distributed throughout the day, and uniform over the entire distance range considered. Probabilities of radio contacts for the second case considered are shown in Figs. C-2 and C-3. Radio contacts

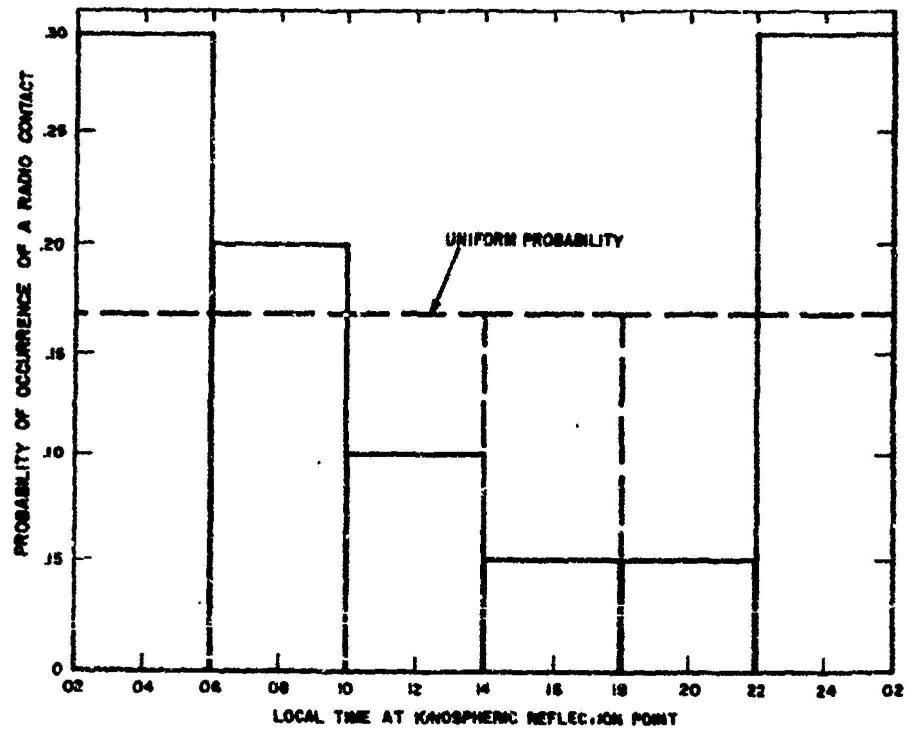

FIG. C-2
ASSUMED PROBABILITY DISTRIBUTIONS OF RADIO CONTACTS OVER THE TIME OF DAY

were assumed to be more probable during night hours. This might correspond to long range bombing missions as were carried out during the early parts of World War II. Transoceanic flights of commercial airlines are also more numerous during the night.

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[1] National Bureau of Standards, Basic Radio Propagation Predictions; Central Radio Propagation Laboratory, Series D.

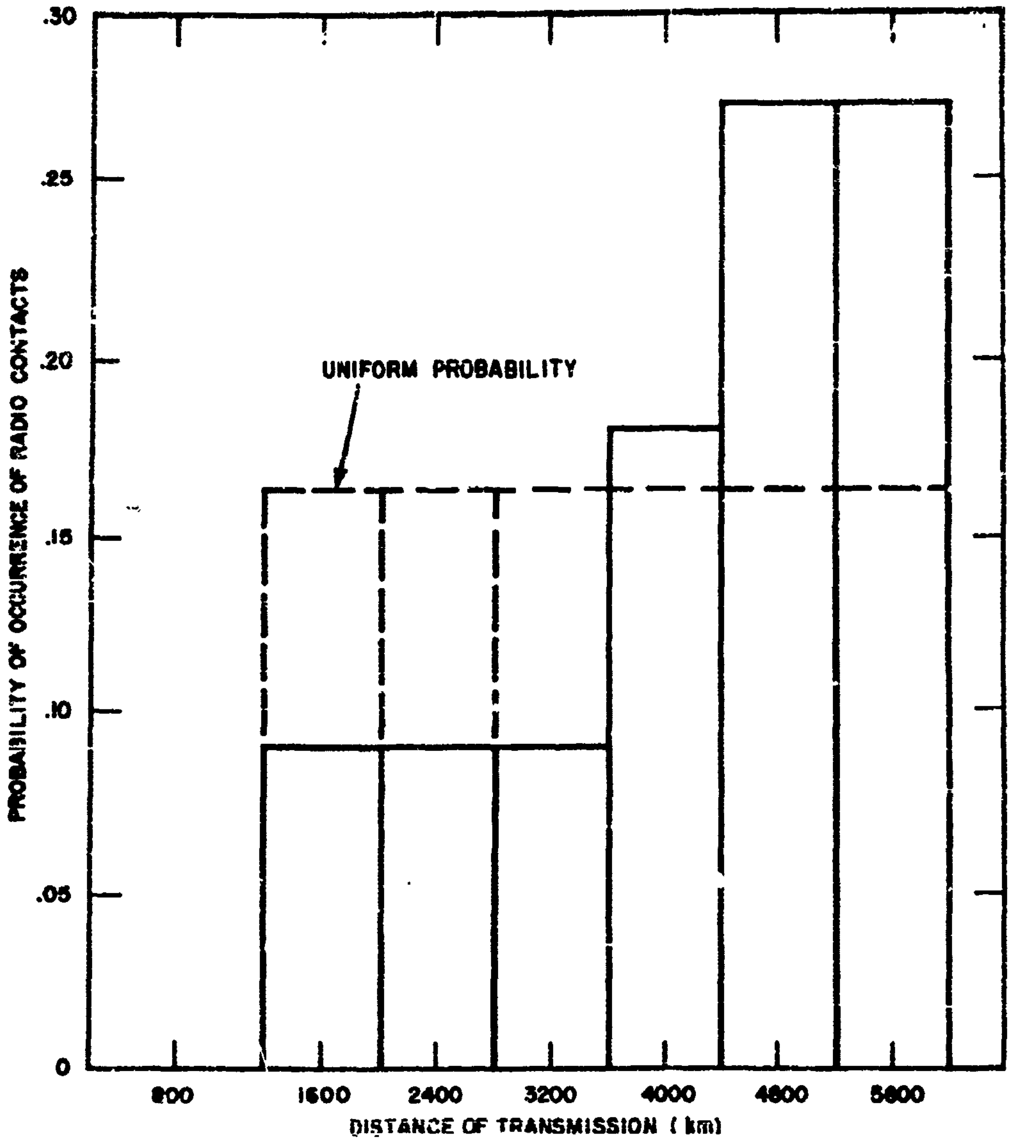

FIG. C-3

ASSUMED PROBABILITIES OF RADIO CONTACTS AS A FUNCTION OF DISTANCE OF TRANSMISSION

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The probability of radio contacts as a function of distance was taken to be zero for distances less than 1200 km, and increased with increasing distances as shown in Fig. C-3. Such a distribution is not solely based on a consideration of the relative number of transmissions over the various distance ranges, but takes account of the relative importance of the messages being transmitted. Thus, ranges of transmission of less than 1200 km may be much more frequent than transmissions over distances beyond that

range. Yet, most of the messages transmitted over such short distances will be of a routine nature, and at very short distances v-h-f or u-h-f facilities can be used as alternate channels. In addition, as discussed before, the reliability of the circuit for short distance transmissions is not greatly affected by the choice of antennas. At the greatest ranges, on the other hand, the system performance is often marginal so that the choice of a proper antenna will improve the system performance. At the same time, reliable transmission of messages at the extreme distance range may be one of the primary requirements of the system. The probability of radio contacts with distance of transmission chosen here was based on such considerations. The azimuthal probability was taken to be uniform, corresponding to the requirements for the most important military uses.

The weighting function, $\omega(\theta,\phi,f)$, of Eq. (C-14), for the case of uniform probability distributions, is shown in Fig. C-4. The vertical angle of transmission was taken as the independent variable while the available frequencies were chosen as parameters. The rapid increase of this function as the vertical angle of transmission approaches the horizontal is not due to focusing, but rather to the sharp increase in noise during the mid-day period. This also accounts for the much larger rise in the function at the higher frequencies which are used for very long distance transmissions during daylight hours.

The weighting function for the case of a larger fraction of nighttime radio contacts, increasing in number with increasing distance, is shown in Fig. C-5. The weighting function for the lower frequencies is larger here than in the case previously considered because of the increased importance of nighttime traffic. In addition, angles of transmission near the horizon are of still higher importance due to the increased stress placed on transmissions over extreme distance ranges.

The weighting functions were combined with the radiation patterns of three different antenna systems on a C-54 aircraft, in accordance with Eq. (C-13). The antennas considered were a wing-cap, tail-cap, and fixed-wire antenna. As before, the factors of merit are given relative to those of the fixed-wire antenna. Figure C-6 shows the results before summation over frequency. As a comparison, the radiation pattern efficiencies of these antennas relative to those of the fixed-wire antenna are also shown in this figure. The useful vertical angle was taken to be ±5 degrees about the horizontal in this comparison, in accordance with the much greater weight given to these angles in the factor of merit. It might be noticed

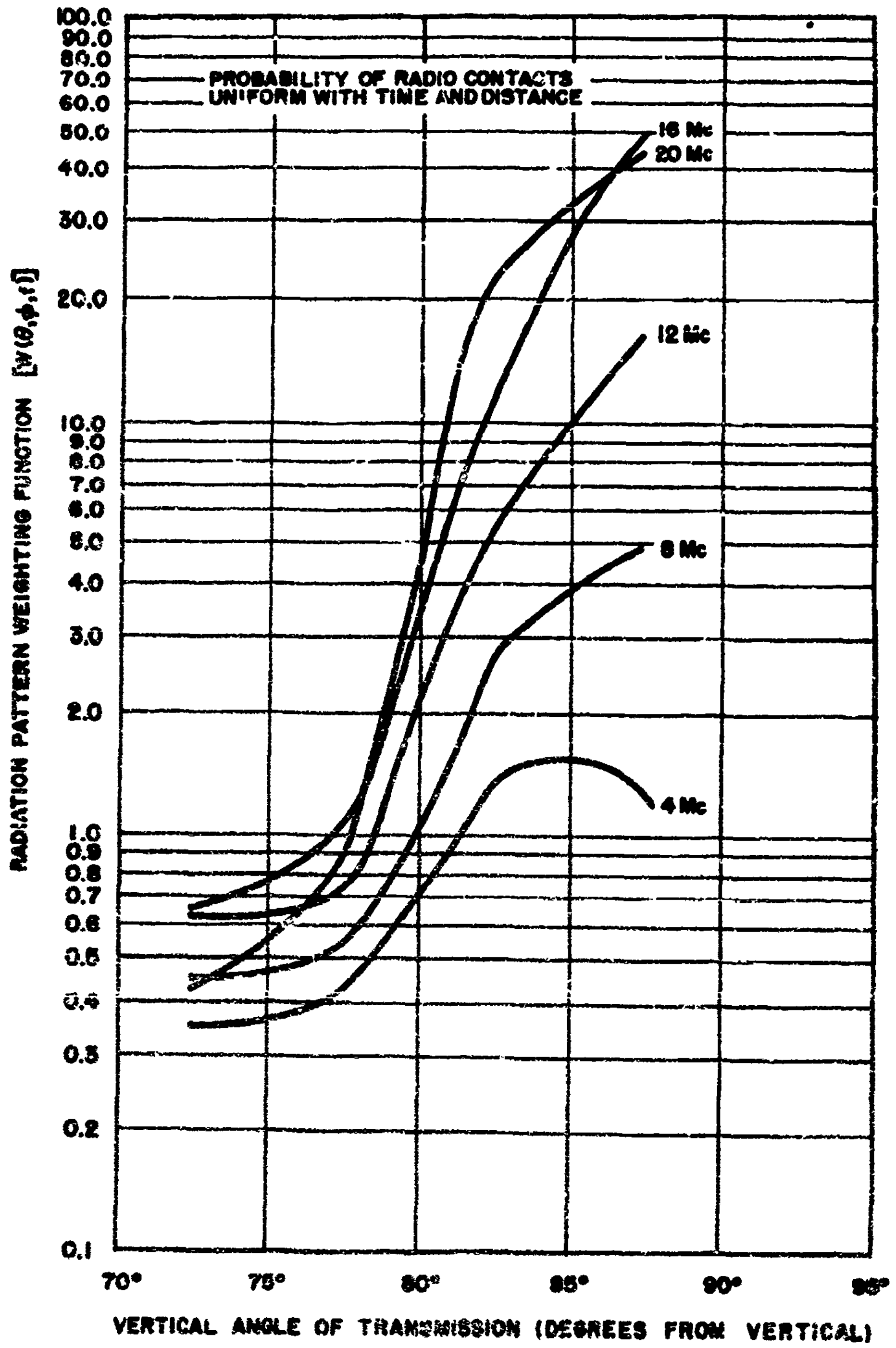

FIG. C-4
RADIATION PATTERN WEIGHTING FUNCTION

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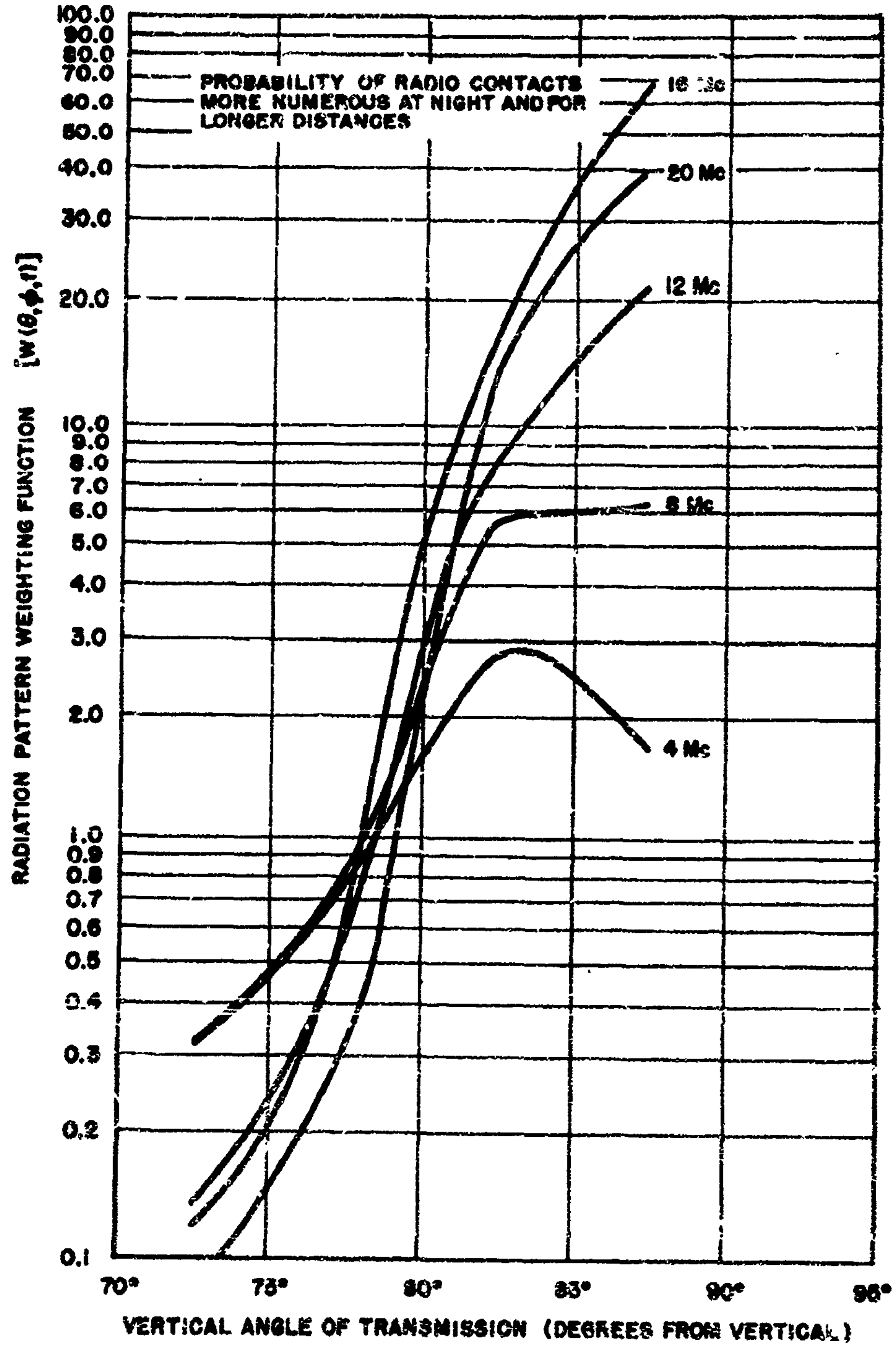


FIG. C-5

RADIATION PATTERN WEIGHTING FUNCTION

that the radiation pattern efficiency corresponds to a weighting function of unity over the useful sector at all frequencies, and zero outside this sector.

The results obtained are seen to be almost identical, despite the use of three such widely differing weighting functions. This is due to the fact that the weighting factor has a finite value over a very narrow range in elevation only. The gain function, on the other hand, is practically constant

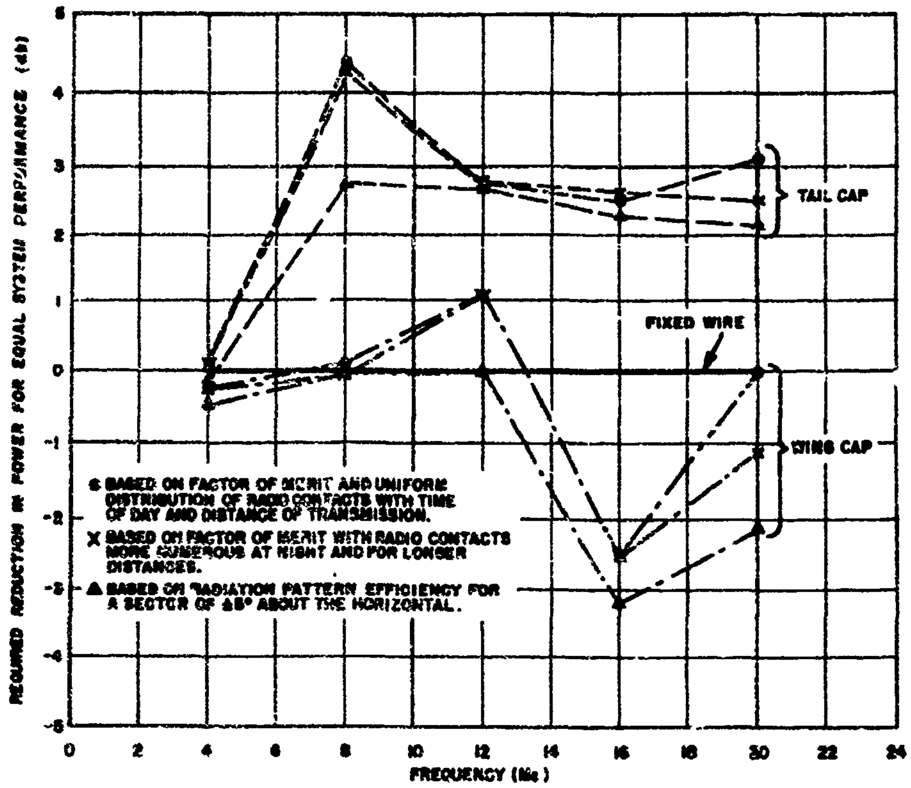


FIG. C-6
COMPARISON OF FLUSH-MOUNTED ANTENNAS WITH FIXED-WIRE ANTENNA ON C-54 AIRCRAFT, AS A FUNCTION OF FREQUENCY

over this narrow region in the vertical plane and may be taken outside the integral in Eq. (C-13). When taking the ratio of the factors, to find the relative standing of the antennas with respect to that of the fixed-wire antenna, the remaining integration over the weighting function then cancels out.

The complete factor of merit for the two cases considered is shown in Table C-I. A comparison with the radiation pattern efficiency again shows nearly identical results. Since the exact evaluation of the weighting function is not only lengthy, but also based on quite far-reaching approximations, such detailed considerations do not seem to be required for h-f aircraft antenna systems evaluation.

TABLE C-I

COMPARISON OF FACTOR OF MERIT WITH
RADIATION PATTERN EFFICIENCY

		Tail-Cap Antenna	Wing-Cap Antenna	Fixed-Wire Antenna
Factor of Merit	Uniform probability of radio contacts with time and distance	185%	87%	100%
	Radio contacts more numerous during night and for longer distances	179%	80%	100%
Radiation Pattern Efficiency	Radiation pattern efficiency averaged over frequency (vertical sector: ±5 degrees about horizontal)	185%	92%	100%

D

APPENDIX D

EVALUATION OF H-F AIRCRAFT ANTENNAS FOR RECEIVING

In Appendix E, a method is described by means of which average articulation scores can be computed from signal-to-noise ratio distributions as observed at the receiving end of the link of which the antenna under test forms a part. It is shown that the average articulation score, $\overline{A}$, taken for reception in all azimuthal directions about the aircraft, is obtained from signal-to-noise ratio distributions averaged over these directions. In symbols:

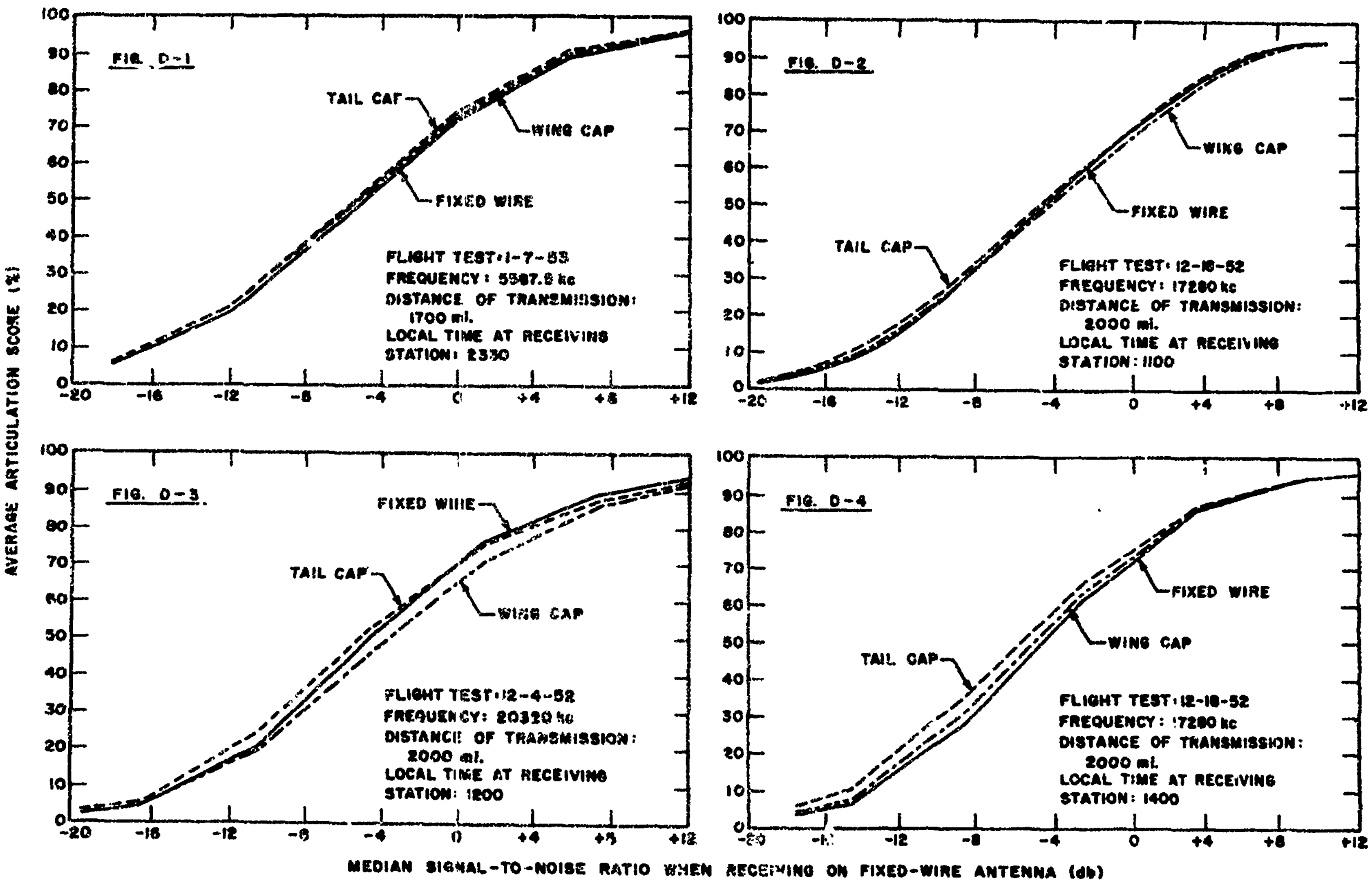
$$\overline{A} = \int_{-\infty}^{+\infty} \frac{dA(u)}{du} \overline{\Phi}(X > u)du, \qquad \text{(D-1)}$$

where $A(u)$ is the articulation score, as a function of the signal-to-noise ratio, u, expressed in decibels. The average signal-to-noise ratio distribution, $\overline{\Phi}(X > u)$ is given by

$$\overline{\Phi}(X > u) = \int_0^{2\pi} p(\phi)\overline{\Phi}_\phi(X > u)d\phi \qquad \text{(D-2)}$$

Here, $p(\phi)d\phi$ is the probability of radio contacts with stations in an azimuthal sector of width $d\phi$, about a direction ϕ with respect to the aircraft. The distribution function, $\overline{\Phi}_\phi(X > u)$, gives the fraction of time during which the signal-to-noise ratio, X, exceeds a level of u decibels when the aircraft has the heading of ϕ, with respect to the transmission path.

Flight test data indicates that the differences between antenna systems are much smaller when aircraft antennas are used in receiving than when they are used in transmitting. This is illustrated by the results of four flight tests summarized in the curves of Figs. D-1, D-2, D-3, and D-4. These curves show average articulation scores computed for simultaneous reception on a tail-cap antenna, a wing-cap antenna, and a fixed-wire antenna, all on a C-54 aircraft. The abscissa for these curves



FIGS. D-1, D-2, D-3, D-4
FLIGHT TEST COMPARISON OF ANTENNA SYSTEMS ON C-54 AIRCRAFT
RECEIVING CASE

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is the median signal-to-noise ratio as recorded over the fixed-wire antenna. Details of the flight test procedure and of the required data analysis are discussed in Appendix F and Appendix G.

Average articulation scores for night time reception on the aircraft at a frequency of 5587.5 kc are shown in Fig. D-2. The performance of the three antennas is seen to be identical under the conditions indicated. The performance is also identical at a frequency of 17,280 kc which was used during a day time test (Fig. D-3). Atmospheric noise under the latter conditions was about 18 db below the noise during the night test. The results of another day test at a frequency of 20,320 kc are shown in Fig. D-3. Atmospheric noise was here about 23 db below that for the case shown in Fig. D-1. Some differences between articulation scores for the three antenna systems can now be observed. The difference, however, is well within the experimental error of the method and apparatus employed in obtaining these curves. As a check, the test on 17,280 kc was repeated, with the results shown in Fig. D-4. The differences found were again within the experimental error of the method of comparison. It can, therefore, be concluded that all aircraft antenna systems sufficiently good to make atmospheric noise the overriding noise of the receiver perform equally well in reception.

Three classes of noise may be distinguished. The first of these reaches the receiver without passing through the antenna matching circuit. Thermal noise of the receiver is of this type. Other locally generated noise may be coupled directly to the antennas. While the intensity of such noise does depend on matching of the antenna impedance to that of the receiver input, it is independent of the far-zone gain of the antenna and of the direction of the transmission path, with respect to the aircraft. Corona discharge noise caused by triboelectric charging of the aircraft (precipitation static) is of this type. As just stated, the third type of noise is atmospheric noise.

Atmospheric noise due to distant thunderstorms appears to be the most important type of noise as far as the h-f liaison system is concerned. Such noise reaches the receiver by way of the sky wave in the same manner as the signal, so that both noise and signal are similarly affected by ionospheric conditions. When operating near the muf, noise originating within the skip zone does not reach the receiver, so that the signal-to-noise ratio is about optimum under these conditions. As a simplified

picture, noise may be imagined to be distributed over a ring-shaped area of the earth's surface, the center of the area being located at the aircraft. The inside diameter of the ring is the skip distance at the frequency of transmission. The outside diameter is not well defined; it corresponds to the distance at which noise sources contribute negligibly to the total received noise. The outside diameter of the ring therefore depends upon the amount of absorption taking place in the ionosphere at the time of observation. The lower this attenuation, the larger will be the total area of the ring and the more intense will be the total amount of atmospheric noise received.*

In order to determine the conditions under which the average articulation score in receiving is independent of the radiation patterns, let it be assumed that all but atmospheric noise is of negligible intensity. Consider the aircraft at a fixed heading ϕ, with respect to the transmission path. Let $n(\Omega, t)$ be the noise power per unit solid angle, Ω, subtended at the aircraft. This noise is, of course, also a random function of the time, t. The noise power received from the direction of the solid angle Ω, is given by

$$\frac{\lambda^2}{4\pi} n(\Omega, t) G(\Omega) d\Omega \qquad \text{(D-3)}$$

where $G(\Omega)$ is the gain function of the aircraft antenna and λ is the wavelength to which the receiver is tuned. The total received noise power is therefore

$$N(t) = \frac{\lambda^2}{4\pi} \int_{\Omega_N} n(\Omega, t) G(\Omega) d\Omega \qquad \text{(D-4)}$$

the integration being carried out over all the angular sectors, Ω_N, from which noise arrives at the aircraft. A system equivalent to that of Eq. (D-4) may be imagined as consisting of an isotropic radiator with noise of average intensity

$$\overline{n(t)G} = \frac{1}{\Omega_N} \int_{\Omega_N} n(\Omega, t) G(\Omega) d\Omega \qquad \text{(D-5)}$$

distributed over the sector Ω_N.

* At night, when absorption is very low, there may be several such rings corresponding to the various numbers of hops of the noise paths.

Since $n(\Omega,t)$ and $G(\Omega)$ are independent of each other, the average of their product equals the product of their averages. Or, in symbols:

$$\overline{nG} = \bar{n}(t)\bar{G}_{\Omega_N} \tag{D-6}$$

where all the averages must be taken over the solid angle Ω_N. Substituting Eqs. (D-5) and (D-6) into Eq. (D-4), the total received noise becomes

$$N(t) = \frac{\lambda^2}{4\pi}\Omega_N \bar{G}_{\Omega_N}\bar{n}(t) \tag{D-7}$$

The arriving signal is also distributed over some solid angle sector Ω_s differing in general from the sector over which the noise arrives. Let $s(\Omega,t)$ be the signal power per unit solid angle. Proceeding in exactly the same manner as for the evaluation of the received noise power, the total signal power is found to be

$$S(t) = \frac{\lambda^2}{4\pi}\Omega_s \bar{G}_{\Omega_s}\bar{s}(t) \ . \tag{D-8}$$

The signal-to-noise ratio is then given by the ratio of Eqs. (D-8) and (D-7) as

$$\frac{S}{N} = \frac{\Omega_s}{\Omega_N}\frac{G_{\Omega_s}}{G_{\Omega_N}}x(t) \tag{D-9}$$

where

$$x(t) = \frac{\bar{s}(t)}{\bar{n}(t)} \tag{D-10}$$

While the noise may be expected to arrive over a wide sector in azimuth -- of the order of 90 degrees or more -- the signal will usually arrive from a single azimuthal direction only. Let α be the range in ϕ over which noise arrives, and β be the angle between the signal path and the edge of the noise band. These angles are illustrated in Fig. D-5. The average gains of Eq. (D-9) can then be written as:

$$\Omega_t \bar{G}_{\Omega_t} = \int_{\theta_1}^{\theta_2} G(\theta,\phi) \sin \theta d\theta, \qquad \text{(D-11)}$$

and

$$\Omega_N \bar{G}_{\Omega_N} = \int_{\phi+\beta-\alpha}^{\phi+\beta} \int_{\theta_1'}^{\theta_2'} G(\theta,\phi') \sin \theta d\theta d\phi' . \qquad \text{(D-12)}$$

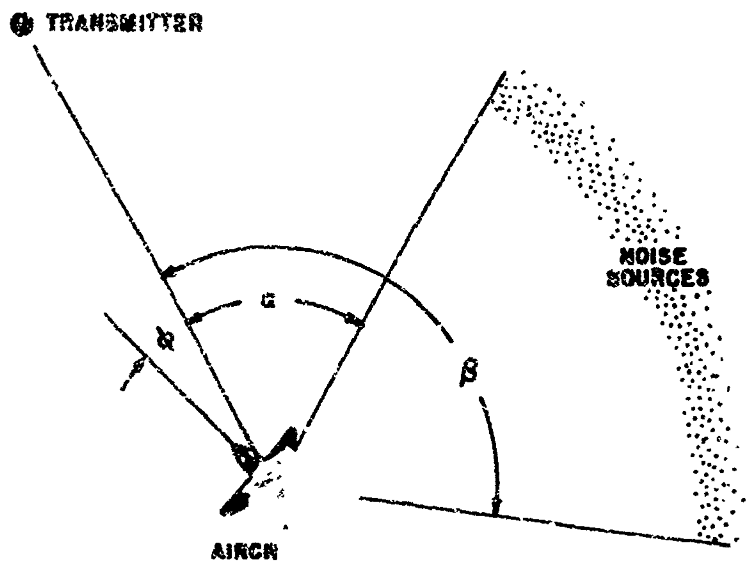

FIG. D-5

RELATIVE LOCATION OF GROUND-BASED TRANSMITTER, AIRBORNE RECEIVER, AND ATMOSPHERIC NOISE SOURCES

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Assume further that both the signal and noise arrive over the same vertical sector θ_1 to θ_2, i.e. $\theta_1 = \theta_1'$ and $\theta_2 = \theta_2'$, and let

$$\int_{\theta_1}^{\theta_2} G(\theta,\phi) \sin \theta d\phi = \bar{G}(\phi) . \qquad \text{(D-13)}$$

ρ

The signal-to-noise ratio can then be expressed as the product of two functions:

$$\frac{S}{N} = f(\phi)x(t) \tag{D-14}$$

where

$$f(\phi) = \frac{\bar{G}(\phi)}{\int_{\phi+\beta-\alpha}^{\phi+\beta} \bar{G}(\phi')d\phi'} \tag{D-15}$$

We now return to Eq. (D-1) to determine the conditions under which the average articulation score is independent of the function, $f(\phi)$, which contains all the radiation pattern information of the receiving antenna. Let

$$X = 10 \log_{10}\frac{S}{N}$$

Equation (D-14) leads to

$$X = z(\phi) + y(t) \tag{D-16}$$

where

$$z(\phi) = 10 \log_{10} f(\phi)$$

$$y(t) = 10 \log_{10} x(t) \tag{D-17}$$

The distribution function, $\bar{\Phi}_{\phi}(X>u)$ is simply a function of the variable u, i.e.

$$\bar{\Phi}_{\phi}(X>u) = F(u) \tag{D-18}$$

A typical example of such a distribution is shown in Fig. D-6. Making use of Eq. (D-16), one obtains

$$\bar{\Phi}_{\phi}(y>u-z) = F(u-z) \ . \tag{D-19}$$

Note that $\bar{\Phi}_{\phi}(y>u-z)$ is a time distribution of the signal-to-noise ratio which is assumed to be constant for the duration of the tests, that is

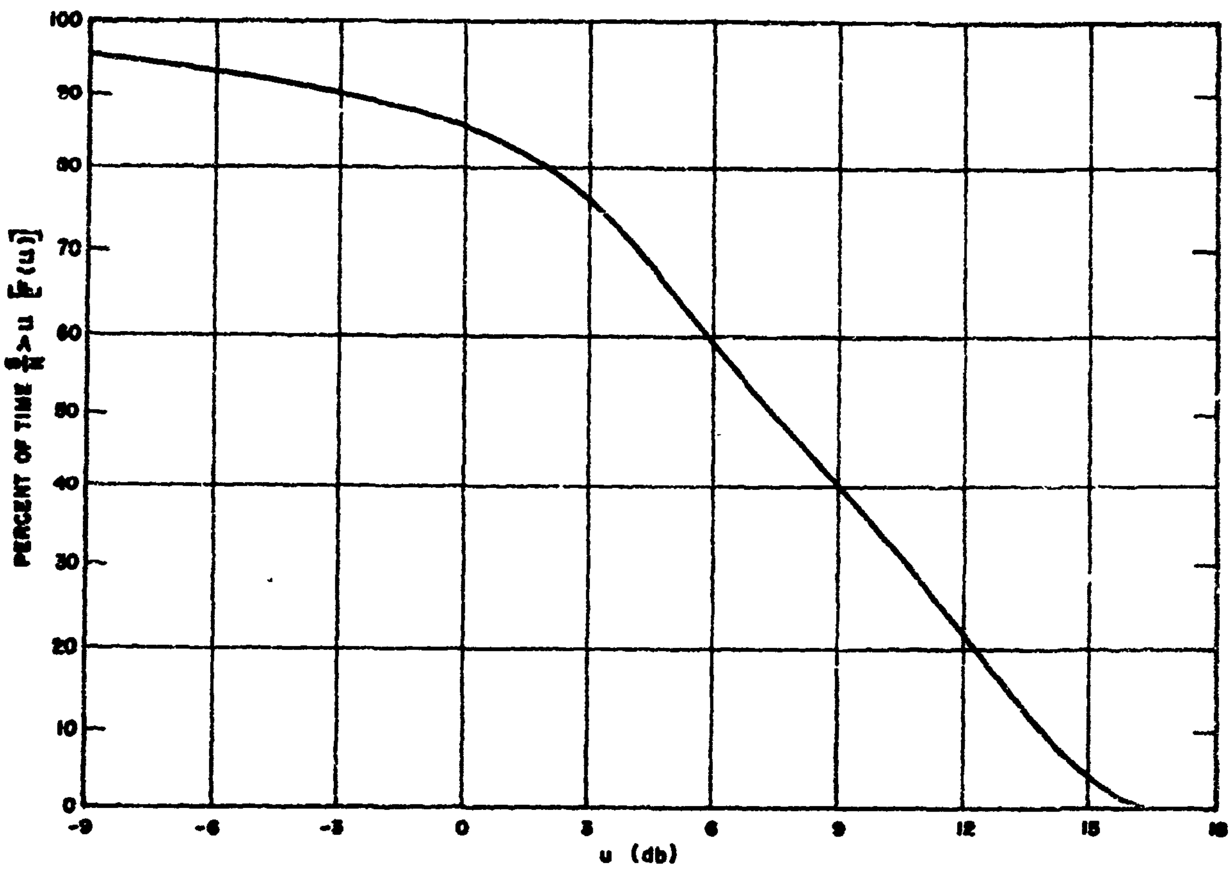

FIG. D-6

DISTRIBUTION OF SIGNAL-TO-NOISE RATIO AS RECORDED ON AIRCRAFT

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for the time required to sample a sufficient number of ϕ-directions. Different angles, ϕ, between aircraft and transmission path simply move the distributions, as shown in Fig. D-6, to the left or right in accordance with Eq. (D-19). Equation (D-2) can now be written as

$$\overline{\Phi}(X>u) = \int_0^{2\pi} p(\phi)F(u-z)d\phi \qquad \text{(D-20)}$$

The average over the variable ϕ is now changed to one over the variable z, which is functionally related to ϕ, i.e.

$$p(\phi)\,|d\phi| = p_1(z)\,|dz| \qquad \text{(D-21)}$$

ρ

The average articulation score is then given from Eq. (D-1) by

$$\bar{A} = \iint_{-\infty}^{+\infty} \frac{dA(u)}{du}\, p_1(z) F(u-z)\, dZ du \tag{D-22}$$

This equation shows that the average articulation scores are independent of the radiation patterns only if the integration of Eq. (D-22) does not depend on the functional form of the factor $p_1(z)$. The dependence of the average articulation score $\bar{A}$ on the function $p_1(z)$ is most conveniently investigated by performing numerically the integrations required by Eq. (D-22). The radiation patterns of a fixed-wire antenna and a tail-cap antenna of a C-54 aircraft were analyzed for this purpose. Uniform probability of radio contacts in azimuth was assumed, and both noise and signal were taken to arrive over a vertical sector of ±15 degrees about the horizontal. It will be noted that when $p(\phi)$ is independent of ϕ, $p_1(z)$ is simply the probability density of the function, z, given by Eqs. (D-15) and (D-17).

The azimuthal spread of the directions of arrival of atmospheric noise depends on the geographical location of the receiver. The directions of the signal paths, relative to the directions of arrival of noise, are arbitrary, since any combination of these directions may occur in the liaison system. Several different cases were therefore assumed in order to examine the effect of varying these two angles.

For the first case considered, noise sources were assumed to be spread over a sector of 100 degrees, and the direction of arrival of the signal coincided with that of noise arriving from one edge of the noise band. This corresponds to the following values of the angles α and β, as shown in Fig. D-5:

$$\alpha = -100^\circ \qquad \beta = 0^\circ$$

Figure D-7 shows the probability densities of the function z for the two antennas under the stated conditions. Patterns taken at a frequency of 19 Mc were chosen for these computations. The peculiar shape of the probability density functions is due to the limited number of lobes in the patterns of these antennas. While the probability densities of z for the tail-cap antenna and fixed-wire antenna are similar, they are not identical.

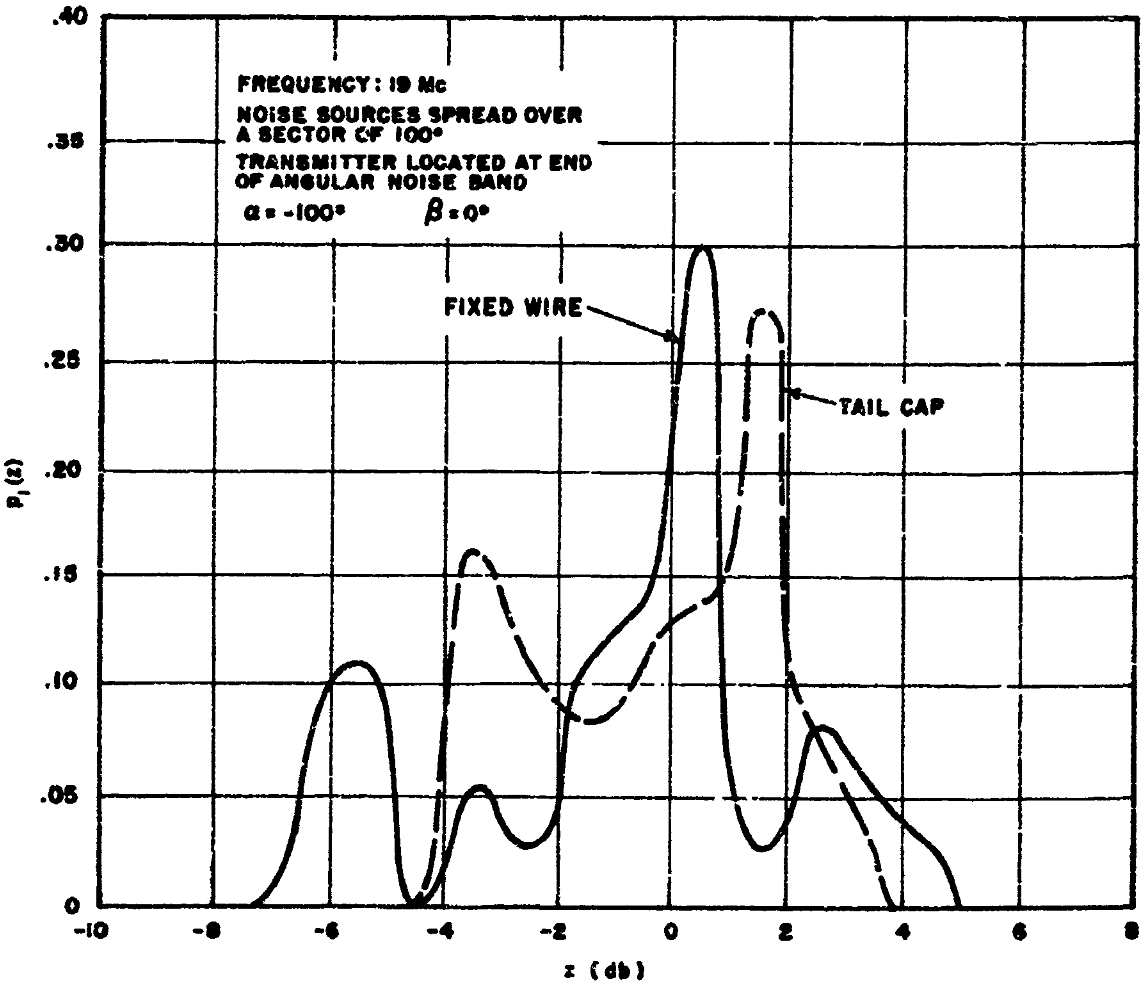

FIG. D-7

PROBABILITY DENSITY OF THE FUNCTION z FOR A FIXED-WIRE AND TAIL-CAP ANTENNA ON C-54 AIRCRAFT

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When the integrations of Eq. (D-23) are carried out, however, using these probabilities, the curves of Fig. D-8 are obtained, which give the relationships between average articulation score and median signal-to-noise ratio. The function, $F(u-z)$, taken for the computations, is the one shown in Fig. D-6. It should be noted that this curve moves to the right or left as the effective radiated power in the direction of the receiver is increased or decreased, while the shape of the distribution remains unchanged. It is therefore possible to obtain articulation scores from this one distribution, which correspond to many different

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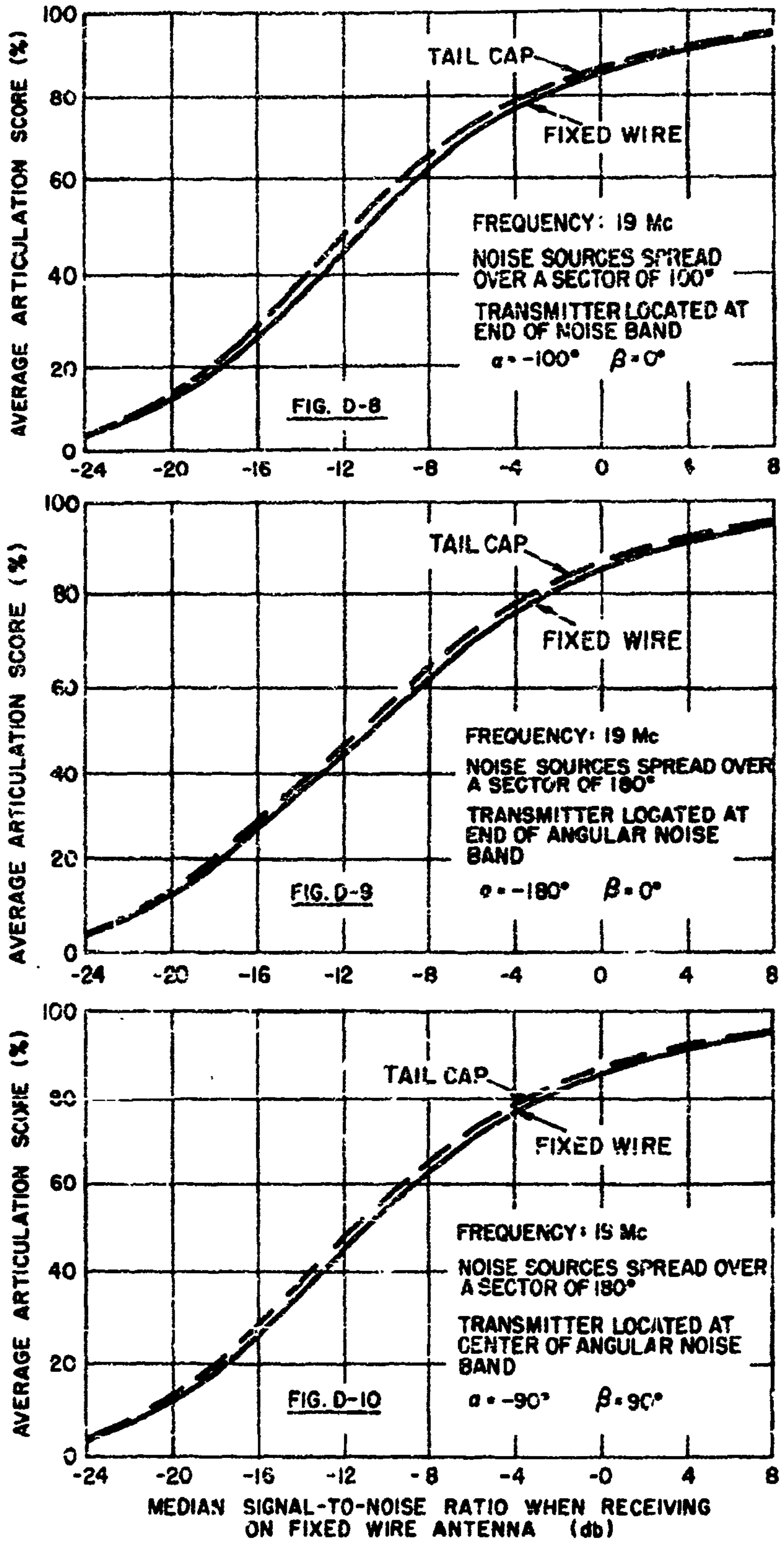

FIGS. D-8, 9, 10
AVERAGE ARTICULATION SCORES COMPUTED FOR RECEPTION ON THE AIRCRAFT

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signal levels at the receiver. This was done in computing the average scores shown in Fig. D-8. The relation between average articulation scores and median signal-to-noise ratio computed by these methods and under the assumptions presented in this appendix, should be compared with the curves of Fig. D-3, obtained by actual experiment. The results obtained in the two cases are in excellent agreement.

Two other cases were considered, using the same radiation patterns, in order to test the importance of the extent of the sector over which noise arrives, and the importance of the relative directions of arrival of noise and signal. In Fig. D-9 the computed average articulation scores are shown as a function of median signal-to-noise ratio when the noise sector extends over 180 degrees in azimuth, and the signal source is located at one end of the angular noise band. The third case considered is shown in Fig. D-10. Here the angles of arrival of the noise again spread over 180 degrees, but the transmitter is located in the direction of the center of this sector. A comparison of Figs. D-8, D-9, and D-10 shows no significant difference for these three cases.

Finally, let us briefly consider the case of transmission from the aircraft to a ground station. In this case, the noise at the receiver is independent of the aircraft antenna radiation patterns and of aircraft orientation. The signal-to-noise ratio at the receiver may therefore be expressed as

$$\frac{S}{N} = k\overline{G}(\phi)x(t) \qquad \text{(D-23)}$$

in accordance with Eq. (D-14); k being simply a constant depending on the receiving antenna pattern and the location of the receiver, with respect to the noise sources. The gain function in Eq. (D-23) is that of the transmitting antenna on the aircraft. If we let

$$g(\phi) = 10 \log_{10} \overline{G}(\phi) \qquad \text{(D-24)}$$

the average articulation score is seen to be given by

$$\overline{A} = \iint_{-\infty}^{+\infty} \frac{dA(u)}{du} p_1(g)F(u-g)du\,dg \qquad \text{(D-25)}$$

where $p_1(\phi)$ is the probability density of the function ϕ, at least for the case of uniform azimuthal distribution of radio contacts.

Average articulation scores were computed using Eq. (D-25) and the distribution of Fig. D-6. The same radiation patterns were analyzed for this purpose, as those considered for the receiving case. The results shown in Fig. D-11 demonstrate that greater differences between articulation scores may be expected when using different antenna systems in

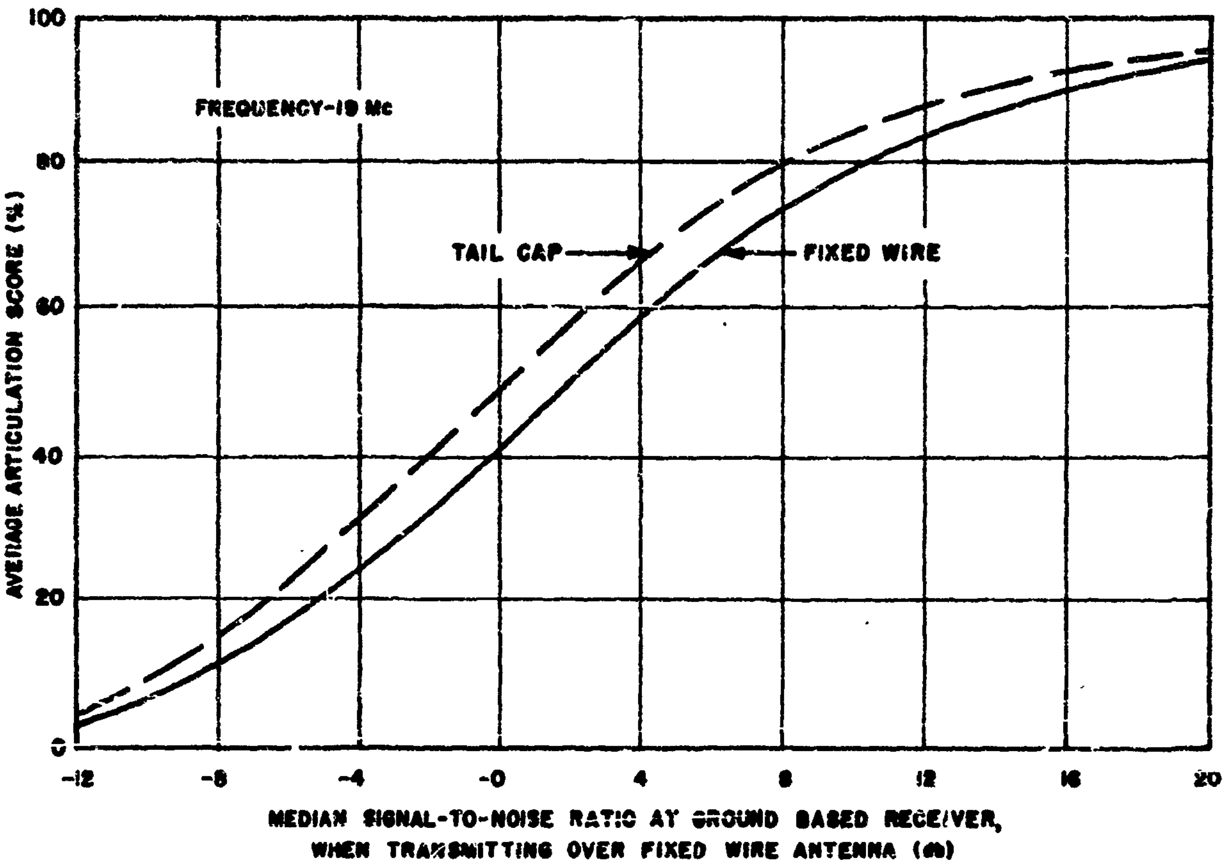

FIG. D-11

AVERAGE ARTICULATION SCORES COMPUTED FOR TRANSMISSION FROM AIRCRAFT

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transmitting, than there would be in a comparison of these antennas in receiving, as long as atmospheric noise is dominant in the system.

If local noise at the aircraft overrode the effect of atmospheric noise, the receiving and transmitting cases would be equivalent except

for the fact that the constant k in Eq. (D-24) would be different for each antenna. This constant depends on the degree of coupling of local noise to the antennas, which in general may be expected to change considerably with the type of antenna and its location on the aircraft. When atmospheric noise is insignificant, therefore, the articulation scores observed when receiving with the various antennas would vary more than when transmitting over these antennas. The analysis presented here therefore indicates that, ordinarily, the major part of the noise received on an aircraft at high frequencies is indeed atmospheric noise.

APPENDIX E

THE MEASUREMENT OF PERFORMANCE OF VOICE - MODULATED COMMUNICATION SYSTEMS

A. INTRODUCTION

A quantitative measure of the performance of a voice-modulated communication system can be obtained by counting the number of speech units correctly identified by a group of listeners at the receiving end of the link. The result is usually stated in terms of an articulation score which is given by the percentage of items correctly recorded.[1] All such scores are relative, contingent on the use of specific announcers, microphones, amplifiers, earphones, listeners, and other similar factors which must be kept as uniform as possible during articulation tests. The quantity of interest is therefore not the actual articulation score but the change in score obtained by varying one of the parameters of the system.

In the present case, the effect of different aircraft antennas on the performance of the h-f air-to-ground liaison system is to be determined. Transmissions may consist of clear speech, code words, or more often, words of the phonetic alphabet. Articulation scores are therefore a suitable measure of system performance. As already stated, the quantity of importance is the change in articulation score when different antennas are used while all the other parameters, as well as the test procedure, are kept constant.

Air-to-ground and ground-to air communications take place over different directions with respect to the aircraft. The transmissions are by sky wave and are thus subject to the constantly varying conditions of the ionosphere. It is apparent, then, that in addition to standardizing the vocabulary, announcers, listening crew, and the equipments used for the articulation tests, an average of many such tests must be taken, corresponding to the different possible communication links.

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[1] J. P. Egan, Articulation Testing Methods, OSRD Report No. 3802, Psycho-Acoustic Laboratory, Harvard University.

Statistically, ionospheric conditions are constant over periods of about one hour, except during sunset and sunrise. For the case under discussion, therefore, articulation tests using all the antennas which are to be compared must be completed within this time. As explained below, in the procedure employed in the studies reported here, the duration of a single test is about three minutes. When several antennas are to be compared for many different orientations of the transmission paths with respect to the aircraft, the time required for tests on the antennas in sequence will usually exceed the period of stable ionospheric conditions. Simultaneous testing of the several h-f antenna systems on the aircraft is therefore required.

Articulation scores are based on transmissions of special word lists. In the tests conducted here, these lists consisted of fifty monosyllabic words. Words of a list are carefully selected for phonetic balance and are also balanced for ease of identification under difficult conditions. Articulation scores must therefore be based on reception of an entire list; scores based on only part of the lists will lead to erroneous results. For articulation test therefore, separate equipments must be used with each of the antennas, providing as many parallel channels as there are antennas. Alternately, some kind of time sharing would have to be devised, whereby the antennas are connected in turn to a single receiver or transmitter at a fast enough rate that intelligibility of reception is not seriously affected. Both of these schemes lead to considerable difficulties in instrumentation. Time sharing of receiving or transmitting equipment would require not only extremely rapid switching at radio frequencies, but also synchronous switching of the receiver output to as many recording channels as there are antennas. For the first scheme, a number of identical equipments would be needed, all adjusted to give the same transfer characteristics. Furthermore, coupling between these antennas may be strong enough at some frequencies to invalidate the results obtained

In order to overcome these difficulties, an indirect method for obtaining articulation scores was devised. This method is based on the relationship which exists between the signal-to-noise ratio at the receiver output and articulation scores. Knowing this relationship and the statistical distribution of the signal-to-noise ratio measured for a given time interval, the average articulation scores which would have been observed for this same period can be computed. This indirect method for finding average articulation scores has another great advantage. Articulation

scores depend, among other factors, on the transmitted power, the gain of the ground-based antenna, and on the attenuation over the transmission path. Having obtained articulation scores for one set of overall signal power levels at the receiver, there is no ready way to estimate the scores which would be obtained for other levels of the received signal power. A separate articulation test would thus be required for every condition of power level which may be encountered in the system. A single signal-to-noise ratio distribution, on the other hand, can be used to compute average articulation scores for any number of possible median signal or noise power levels.

The proposed method for determining average articulation scores is based on several assumptions which are detailed below. In a separate series of tests, the degree of correlation between actual articulation scores and those computed from signal-to-noise ratio distributions was established. After this procedure was shown to be valid, it was applied to the evaluation of a tail-cap antenna, wing-cap antenna, and fixed-wire antenna on a C-54 aircraft, using average articulation scores as a performance measure of the system. These flight tests are discussed in Appendix F.

B. THE DERIVATION OF AVERAGE ARTICULATION SCORES FROM DISTRIBUTIONS OF THE SIGNAL-TO-NOISE RATIO

Articulation scores are functionally related to the signal-to-noise ratio.[1] In the liaison system, which utilizes sky-wave transmission, however, both signal and noise are subject to fading. The direction of the signal path with respect to the aircraft antennas which are to be evaluated also varies more or less randomly throughout the life span of the aircraft, or, in some cases, even for the duration of one flight. System performance is therefore measured by articulation scores averaged over all these conditions.

The signal-to-noise ratio will have a certain distribution in time. If u denotes the signal-to-noise ratio in decibels, the quantity of interest is the density function, $p(y)\,dy$, which expresses the probability that

$$y < u < y + dy$$

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[1] J. P. Egan, *op. cit.*

Let it be assumed that the probability density function, $p(y)$, is stationary, at least for the period of time required to carry out the tests to be described. It is also assumed that the fading rate of the signal is slow in comparison with the duration of transmission of one of the monosyllabic words used for the articulation tests. Let $A(u)$ denote the articulation score for a fixed signal-to-noise ratio of u db. Under these conditions, the average articulation score, $\bar{A}$, which would be observed when random fading is present will be given by

$$\bar{A} = \int_{-\infty}^{+\infty} p(y)A(y)dy \tag{E-1}$$

The distribution function of the signal-to-noise ratio is defined as the probability that this ratio exceeds a given level, y db; and is therefore given by the integral

$$\Phi(u > y) = \int_y^{\infty} p(x)dx \ . \tag{E-2}$$

Using this function and integrating Eq. (E-1) by parts leads to

$$\bar{A} = \int_{-\infty}^{+\infty} \Phi(u > y) \frac{dA(y)}{dy} dy \tag{E-3}$$

If the signal-to-noise ratio depends on another variable, ϕ, which is distributed with a probability density $p_1(\phi)$, a second averaging over this variable has to be performed in order to obtain the average articulation score. The order of the two integrations can be interchanged as long as the two variables are independent. The average articulation score is then obtained from an average distribution function given by

$$\bar{\Phi}(u > y) = \int_{\phi} p_1(\phi)\Phi_{\phi}(u > y)d\phi \ , \tag{E-4}$$

the subscript ϕ indicating the dependence of the function on this variable.

The average articulation score under these conditions is found to be

$$\bar{A} = \int_{-\infty}^{+\infty} \bar{\Phi}(u > y) \frac{dA(y)}{dy} \, dy \qquad \text{(E-5)}$$

The integrations of Eqs. (E-3) or (E-5) make it possible to compute average articulation scores from measurements of the signal-to-noise ratio distribution, provided that the relation between articulation scores and the signal-to-noise ratio is known. Tests performed to obtain this function, and the method used to obtain signal-to-noise ratio distributions will be described next.

C. WORD ARTICULATION IN THE PRESENCE OF WHITE NOISE

The relationship between articulation scores and signal-to-noise ratios forms the basis of the indirect method of measuring articulation scores. The tests which were performed to obtain this function of the signal-to-noise ratio will be discussed in this section.

Briefly, the tests consisted in playing back to a group of listeners recordings of standard word lists mixed with known amounts of noise, and counting the number of words correctly identified for various noise levels. It was stated earlier that articulation scores are not an absolute measure, and have meaning only within the context of the test used to obtain them. It is therefore necessary, in the present case, that the test procedure and equipment resemble the conditions and equipment of the h-f air-to-ground or ground-to-air link under investigation.

One of the most important factors on which articulation scores depend is the type of vocabulary used for the listening tests[1]. Since a large share of the transmissions over the liaison system will consist of code words and words of the phonetic alphabet, monosyllabic words lists were considered to be the most suitable for the present tests. The lists used were prepared and recorded at the Central Institute for the Deaf, St. Louis, Missouri. They consisted of four sets containing fifty words each. Each of these sets, in turn, was recorded in six different word orders. Twenty-

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[1] George A. Miller, "Language Engineering", Journal of the Acoustical Society of America, Vol. 22 pp. 720; November 1950.

four different fifty-word lists were thus available so that the same list had to be repeated only infrequently.[1]

Figure E-1 is a block diagram of the equipment used for the articulation tests. The word lists were re-recorded on magnetic tape, the output of which was amplified and mixed with noise. The combined signal and

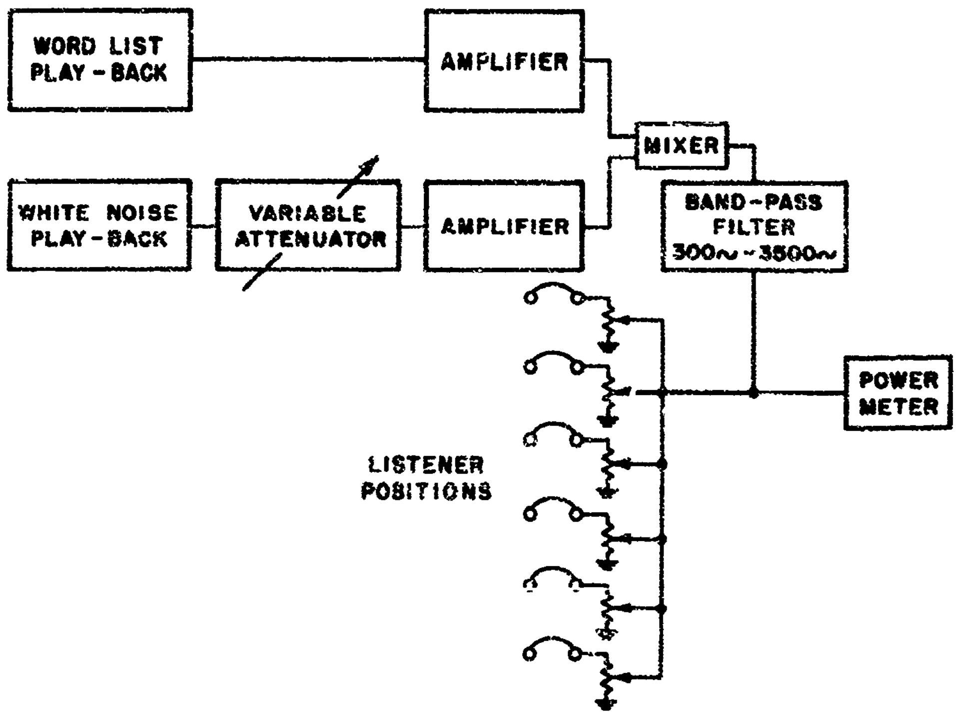

FIG. E-1

ARTICULATION TESTS - EQUIPMENT CONNECTIONS

noise was then brought to six pairs of earphones, after first limiting the audio response to a band of frequencies between 300 cps and 3500 cps, corresponding to the audio characteristics of the receiver to be used with the liaison system. White noise obtained from a recording prepared by Cook Laboratory, Stamford, Conn., was played back into the mixing circuit, over a second tape recorder and amplifier. A calibrated variable attenuator controlled the amount of noise mixed with the signal. The earphones used (AN/B-H-1), were standard Air Force equipment. Each listener position was provided with a separate volume control. The audio response of both

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[1] Davis, Hirsch, Silverman, Reynolds, Eldert, and Benson, "Development of New Materials for Speech Audiometry"; Journal of Speech and Hearing Disorders, Vol. 17, No. 2, pp. 321-337; Sept. 1952

circuits, measured at the output of of the band pass filter, was flat within ±1.0 db over the required range. Figure E-2 is a photograph of the listener crew and the recording equipment.

For the tests, each word was introduced by the carrier phrase "you will say —." During the recording of the lists, this phrase was monitored on a VU-meter. The announcer then read the words as they would naturally follow in the spoken phrase. A 1000 cps calibration tone at the average level of the carrier phrases was recorded at the beginning of each word list. This tone was used as the reference level in determining signal-to-noise ratios. Prior to each test, the gains of the two amplifiers were adjusted so that the power at the output of the band-pass filter for the reference tone equalled that of the noise. This corresponded to a signal-to-noise ratio of 0 db on the scale used here. Other ratios were obtained by varying the setting of the calibrated attenuator. A specially constructed power meter (described in Appendix G) was used in the comparison of signal and noise levels.

The articulation tests were performed in a room partitioned off from the laboratory. While this room was not entirely noise-free, the ambient noise intensity was of insufficient level to leak past the earphones by appreciable amounts and so influence the tests. No attempt was made to simulate the ambient noise conditions which might be encountered in the cockpit of an aircraft.

Listeners were chosen in accordance with the procedure recommended by Egan,[1] and trained by actual listening tests until consistent scores were obtained. Prior to each test, each listener individually adjusted the volume of the signal-plus-noise in his earphones to a comfortable level, in the same way an operator of the actual system would adjust the receiver gain.

Articulation scores as a function of signal-to-noise ratio, obtained in this fashion, are plotted in Fig. E-3. Each point on this curve represents the average of the scores obtained by six listeners. The range in signal-to-noise ratio between 10% articulation and 90% articulation is somewhat smaller than that obtained in the tests described by Miller,[2] where a vocabulary of thirty-two words was used.

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[1] J. P. Egan, op. cit.

[2] G. A. Miller, op. cit.

FIG E-2
LISTENER GROUP FOR ARTICULATION TESTS

This difference in range may be due to the restricted audio frequency band to which the system under discussion is limited. The reference level for 0 db signal-to-noise ratio seems to have been chosen differently for the two experiments.

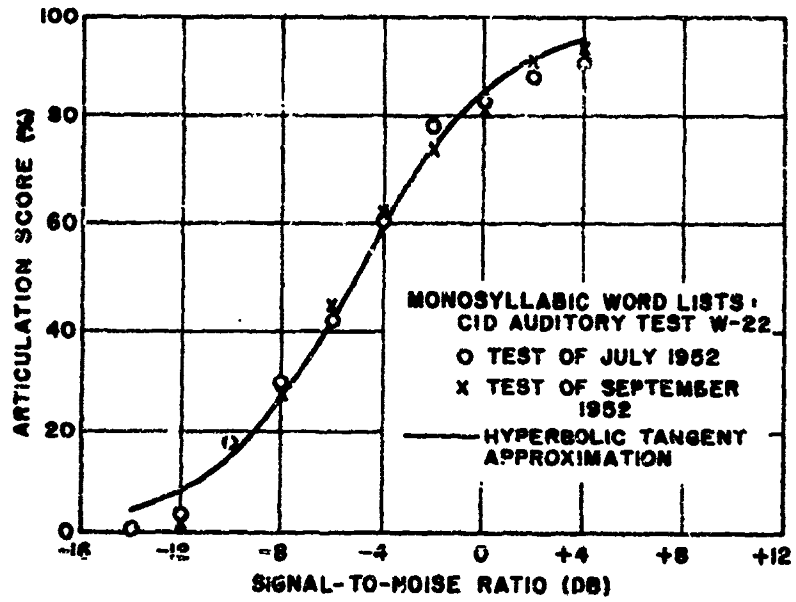

FIG. E-3

ARTICULATION SCORES AS A FUNCTION OF SIGNAL-TO-NOISE RATIO IN WHITE NOISE

Articulation tests were performed over a period of almost a year, during which time some turnover in personnel of the listening crew took place. Each of the replacement listeners was trained to proficiency in identifying words under noisy conditions. Measurements of articulation scores as a function of signal-to-noise ratio in white noise were repeated from time to time as a check on the performance of the group. The resulting scores for a typical repetition are given in Fig. E-2 and are seen to be in excellent agreement with the curve adopted as a standard for the entire test program.

An analytical expression for this function of the signal-to-noise ratio would be convenient for computations of average articulation scores. To a first approximation, this expression may be considered as a linear function of the logarithm of the signal-to-noise ratio over a given range, outside of which it is 0 or 100%, respectively. A closer approximation is given by:

$$A(u) = 50[1 + \tanh 0.174(u+5)] \qquad \text{(E-6)}$$

where u again stands for the signal-to noise ratio in decibels. This is the curve plotted in Fig. E-2.

D. THE MEASUREMENT OF SIGNAL-TO-NOISE RATIO DISTRIBUTION

In order to compute average articulation scores, the distribution function of the signal-to-noise ratio must be known. This function gives the fraction of time for which the signal-to-noise ratio exceeds some given level, and is therefore a function of this level. The signal-to-noise ratio is here defined as the ratio of average signal power to average noise power measured at the output terminals of the receiver, the average being taken over a period corresponding to the time required for the transmission of one of the monosyllabic words.

Accurate determination of signal-to-noise ratios for time intervals corresponding to the duration of about one spoken word is a difficult if not impossible task. Although the word lists are recorded with constant average signal level, the signal power averaged over each word necessarily varies with the word being announced. The noise power also varies continuously; consequently it is not possible to find the signal-to-noise ratio by comparing signal-plus-noise power with noise received alone at a later time. In order to obtain signal-to-noise ratio distributions it was therefore assumed that the signal was adequately represented by a single audio tone. A second tone was added later, since it was feared that selective fading might cause the distributions based on single-tone transmissions to differ markedly from those which would be obtained with a signal consisting of all the frequencies in the band. When the tone levels were adjusted to the average power level of the words on a word list, and with the percentage modulation of the carrier during tone transmissions equal to the average percentage modulation used with the word lists, word list transmissions and tone transmissions were considered equivalent insofar as signal-to-noise distributions were concerned.

To obtain signal-to-noise ratio distributions, a carrier of the proper frequency for transmission over the desired path was modulated with the two audio tones, and the received signal was recorded on magnetic tape. The two tones were adjusted so that each tone represented half of the total signal power. During the transmissions, care was taken to keep both

carrier and tone level constant at the transmitter so that all changes in signal power at the receiver would be due to changes in ionospheric conditions or changes in the direction of the transmission path with respect to the antennas under test. The signal-to-noise ratio distributions were obtained from the recordings by separating signal and noise, using narrow band filters, and comparing them in a differential amplifier. Details of the apparatus which performs this analysis will be found in Appendix G. It may be noted that the audio tones had to be held accurately to their assigned frequencies in order to stay within the pass bands of the filters

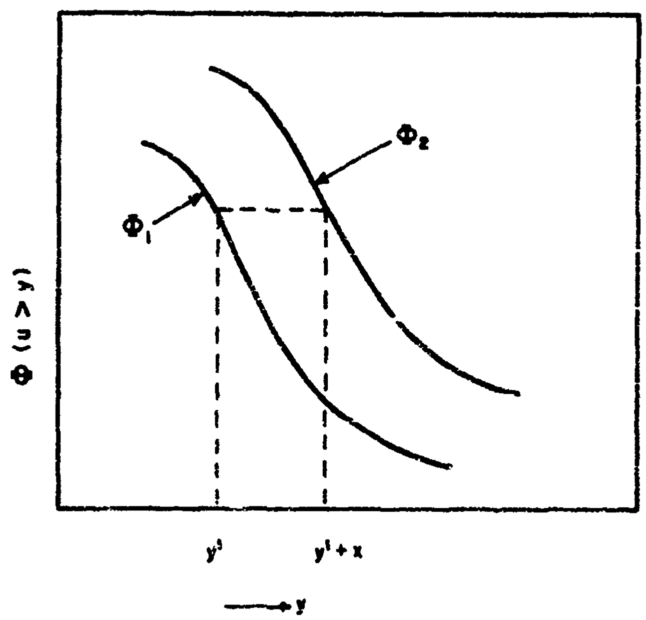

FIG. E-4

SIGNAL-TO-NOISE RATIO DISTRIBUTIONS FOR SIGNALS DIFFERING IN EFFECTIVE TRANSMITTED POWER

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Consider two signals equivalent in all respects, with the exception that the signal power radiated in the direction of the receiver in the second case exceeds that of the first signal. The signal-to-noise ratio distributions will then be identical in shape, and differ by a constant shift only, as illustrated in Fig. E-4. $\bar{\Phi}_1$ and $\bar{\Phi}_2$ are the two distributions, where the signal level for the second distribution exceeds that for the first by x db. If transmission conditions are stationary during the time intervals during which the distributions are obtained, then

$$\bar{\Phi}_1 (u > y) = \bar{\Phi}_2 (u > y + x) .$$

A shift of the distribution curves in the direction of the ordinate is equivalent to a series of measurements at different received signal power levels. Average articulation scores can therefore be computed by the method given in Sec. B of this appendix, for many different assumed

conditions, using only one measured distribution function. This constitutes one of the important advantages of the method just described.

E. CORRELATION BETWEEN ARTICULATION SCORES OBTAINED BY LISTENING TESTS AND ARTICULATION SCORES COMPUTED FROM SIGNAL-TO-NOISE RATIO DISTRIBUTIONS

It was shown in Sec. E-2 that average articulation scores can be computed from signal-to-noise ratio distributions, provided certain conditions are satisfied. It is therefore necessary to show by actual experiment that the suggested method can indeed be used to evaluate articulation scores.

Before proceeding with a description of these tests it will be useful to discuss in more detail the underlying assumptions and approximations of the proposed method for the measurement of articulation scores. Basic to the whole procedure is, of course, the postulate that one, or at most two, audio tones adequately represent the complex audio signal. This will be true if non-linear distortion through the system is small and, of even more importance, if the influence of selective fading is negligible. Observation has shown that the usual type of selective fading has very little effect on speech intelligibility.[1] The use of two audio tones instead of one reduces the effects of selective fading on the simulated signal.

Another assumption which must hold true if average articulation scores are to be computed from signal-to-noise ratio distributions requires that fading be slow in comparison to the time of transmission of a word used for the articulation tests, which means that the fading period should be greater than about 1/6 sec. If the signal-to-noise ratio varies at a faster rate than this, word intelligibility will suffer more severely than would be predicted from simple averaging.[2] Except for disturbed ionospheric conditions, fading rates are of the order of several seconds, or more, so that the stated assumption is usually justified.[3]

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[1] R. K. Potter, "Transmission Characteristics of A Short-Wave Telephone Circuit," Proc. of the I R E., Vol. 18, p. 581. April 1930.

[2] G. A. Miller and J. C. R. Licklider, "The Intelligibility of Interrupted Speech," Journal of the Acoustical Society of America, Vol 22, p. 167; March 1950.

[3] R. K. Potter, op. cit.

It was further assumed that the signal-to-noise ratio distribution is stationary. Actually, ionospheric conditions, and hence the signal-to-noise ratio, are subject to cyclic variations of periods of a day, year, and that of the sunspot cycle, so that the distributions can be considered as approximately stationary only when time intervals of less than about an hour are considered. It is therefore left open to question, just what sub-interval of an hour will furnish a representative sample of the distribution. For the tests to be described, signal-to-noise ratios were recorded over intervals of about three minutes. As will be seen presently, fading with a period greater than three minutes is usually present so that different distributions are obtained for a succession of such intervals. These distributions usually differ more in their relative position than in their shape, however.

Yet another possible source of error in the indirect method of measurement of articulation scores is the use of white noise to establish the relation between signal-to-noise ratios and articulation scores discussed in Sec. B of this appendix. The characteristics of atmospheric noise differ somewhat from those of white noise. Since atmospheric noise is subject to fading, however, it cannot be used to establish the required relationship.

Tests were undertaken to show that the indirect method for the computation of average articulation scores gives results comparable in accuracy to those obtained from actual listening tests. For this purpose, radio station AF5XE at Wright-Patterson Air Force Base, Dayton, Ohio alternately transmitted word lists and three minute periods of carrier modulated by the two audio tones. The nearest available frequency below the optimum frequency predicted for the path was chosen for transmission except when interference from adjacent signals made the use of lower frequencies mandatory. The same word lists and recordings were used for these transmissions as for the tests discussed in Sec. E of this appendix, in which the relationship between articulation scores and signal-to-noise ratios was established. It was pointed out earlier that short periods of a 1000 cycle note recorded with the word lists indicate the average signal level at which the words were announced. The two audio tones used for the tone period transmissions were adjusted so that their combined power equalled the average signal power of the word lists, and each tone singly carried half of this power. The average percentage modulation of the carrier, when word lists were transmitted, was also the same as the modulation used for transmission of the two audio tones.

The transmissions were received at Palo Alto, California and were recorded on magnetic tape. The word lists were then played back to the trained group of listeners, to obtain articulation scores. The equipment used for these articulation tests was essentially the same as that shown in Figs. E-1 and E-2. In this case, of course, no additional white noise had to be added to the word lists recorded over the Dayton-Palo Alto circuit. The periods of audio tone recording were analyzed to obtain signal-to-noise ratio distributions from which average articulation scores could be computed by the use of Eq. (E-3) and the curve shown in Fig. E-3.

It is apparent from the relationship between articulation scores and signal-to-noise ratio that these scores change most rapidly when the signal-to-noise ratio is in the neighborhood of 50% articulation. Changes in signal-to-noise ratio are unimportant if they take place above the value required for 100% articulation, or below the point where none of the words can be identified. For maximum sensitivity of the tests, it was therefore necessary to adjust the transmitter output power to a point where roughly half the transmitted words became intelligible.

Transmissions from Wright-Patterson Air Force Base, of word lists and equivalent audio-tone periods as just described were recorded at Palo Alto over a period of about four months during the summer and fall of 1952. About forty half-hour periods of such records were analyzed. Each of these periods contained four word lists and four tone periods. The signal-to-noise distributions obtained for a typical half-hour period are shown in Fig. E-5. While the variations about the average value are approximately the same for the four distributions, the average signal-to-noise ratio changed considerably from one recording period to the next. This change indicates simultaneous fading of signal and noise with a period of several minutes. It should be remembered that word lists were transmitted between the various dual-tone transmissions, so that there is a time interval of about six minutes between the beginnings of successive tone periods.

The large variations in mean signal-to-noise ratio for the different recording periods make it necessary to interpolate when comparing articulation scores obtained by listening tests with those computed from the signal-to-noise ratio distributions. This is illustrated in Fig. E-6 which gives the results of two half-hour recordings. Articulation scores are plotted at equal intervals along a time base, corresponding to the

three-minute periods of alternate transmission of tone-periods, (T), and word lists, (W). Two curves are obtained, one by straight-line interpolation between successive articulation scores computed from signal-to-noise ratio distributions, the other by joining the points obtained as the result of listening tests. Differences between the two curves were then tabulated for all available data. Each measured value on either curve was used as a point of observation in obtaining these differences.

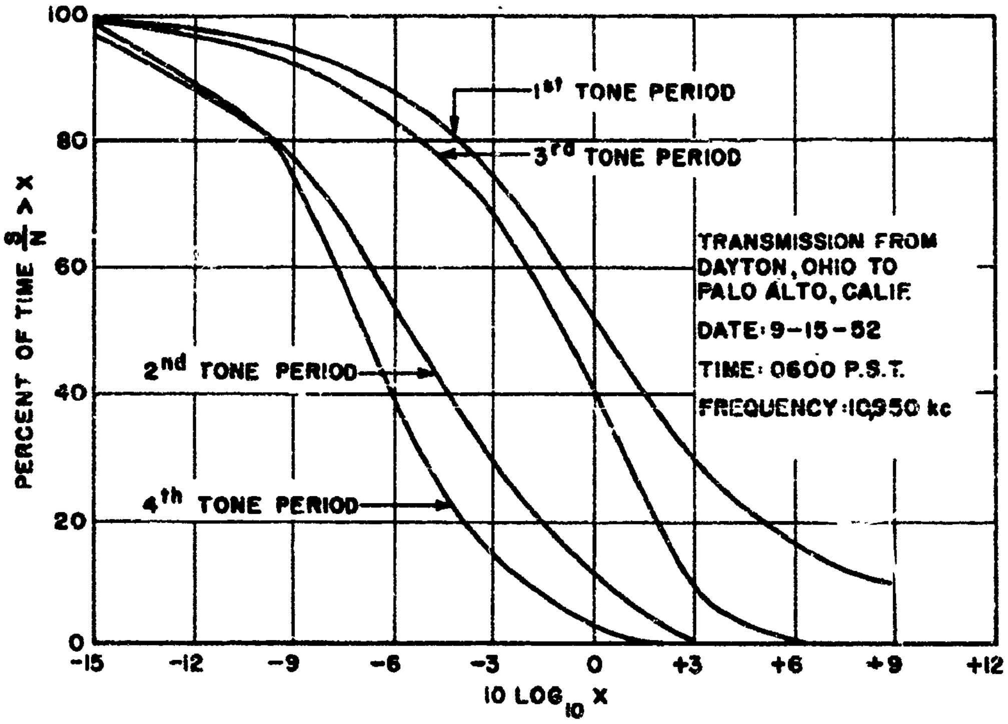

FIG. E-5

DISTRIBUTION OF SIGNAL-TO-NOISE RATIO OVER SKY-WAVE PATH

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In Fig. E-7 the distribution of the differences between articulation scores obtained by listening tests and those computed from signal-to-noise ratio distributions has been plotted on probability paper. The distribution is normal, with an average value of zero and a standard deviation of 12% in articulation score. It should be noted that this data is based on a single set of listening tests using a crew of six. Repeated playbacks of the same lists showed a standard deviation of about 5% in measured articulation score.

These results demonstrate that signal-to-noise ratio distributions can be used to compute average articulation scores under conditions of

normal fading and in the absence of man-made interference. The crowded conditions of the h-f band made it difficult to locate clear channels, especially at night, and it may be supposed that similar difficulties will be experienced in the actual use of the liaison system. Insofar as the dual-tone transmissions are concerned, adjacent channel interference

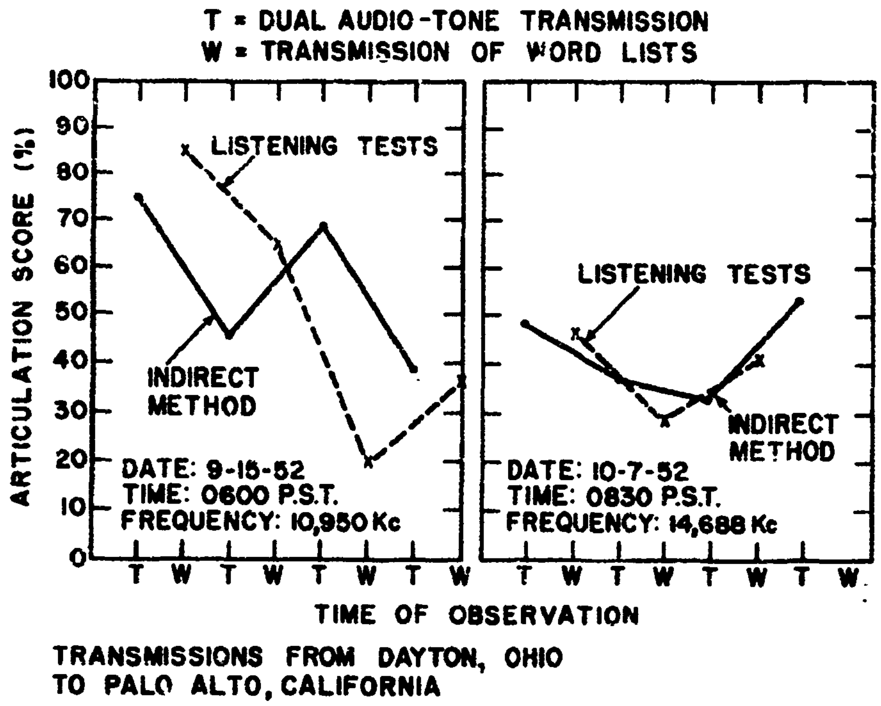

FIG. E-6

COMPARISON BETWEEN ARTICULATION SCORES OBTAINED BY LISTENING TESTS AND THOSE COMPUTED FROM SIGNAL-TO-NOISE RATIO DISTRIBUTIONS

not only increases the overall noise level but also distorts the signal-to-noise ratio distributions in comparison with those obtained in the presence of atmospheric noise alone. While this will tend to lower the computed values of articulation score, it will actually have a much more deleterious effect on the intelligibility of speech transmission. Close correlation between the two methods can no longer be expected, therefore, when such type of interference is encountered.

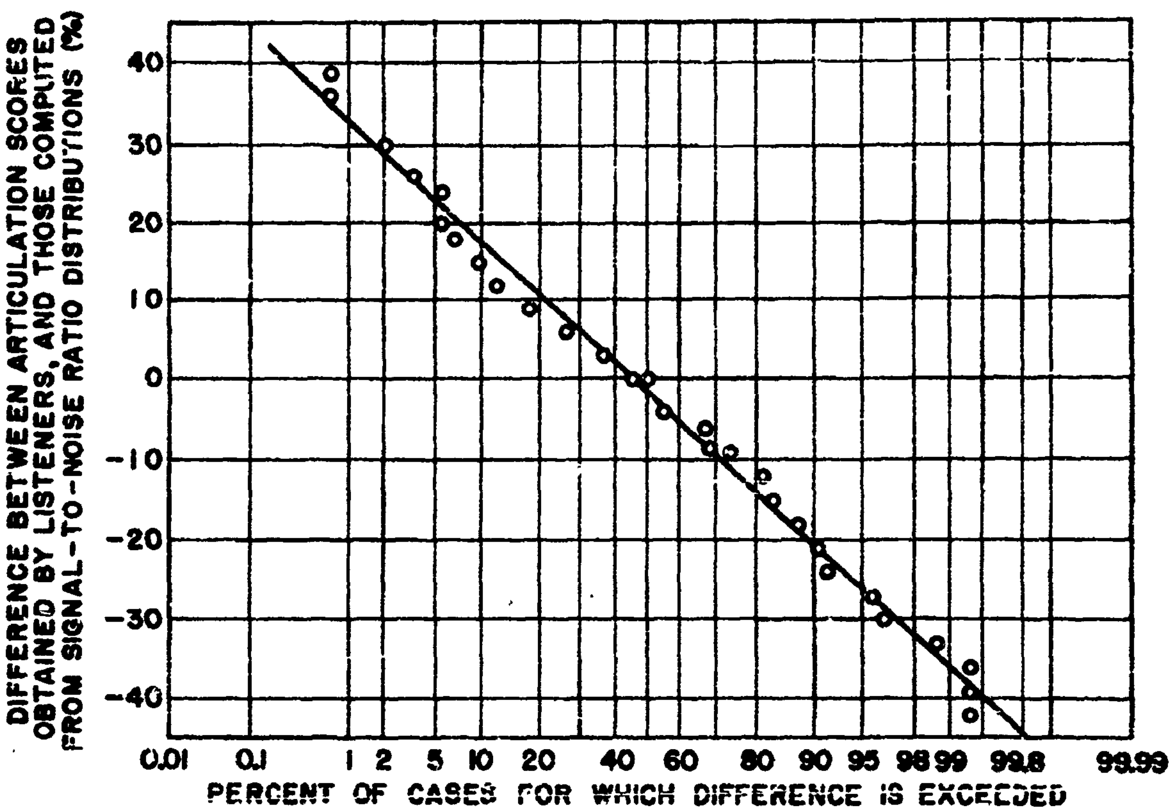

FIG. E-7

DISTRIBUTION OF DIFFERENCE BETWEEN ARTICULATION SCORES COMPUTED FROM SIGNAL-TO-NOISE RATIO DISTRIBUTIONS, AND SCORES OBTAINED BY DIRECT LISTENING TEST

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APPENDIX F

FLIGHT TESTING OF THE H-F LIAISON SYSTEM*

A. INTRODUCTION

This appendix is a description of a series of flight tests conducted with a C-54 aircraft to compare the performance of airborne liaison antennas. Three antennas were compared - an isolated tail-cap, an isolated wing-cap, and a fixed-wire antenna.

The method of evaluation (Appendix E) is based on an indirect determination of articulation scores from the distributions of received signal strength and received signal-to-noise ratios. The evaluation based on the signal strength distributions corresponds to the case where the aircraft transmits to the ground station, while that based on signal-to-noise ratios corresponds to the case where the aircraft is receiving. The performance of the air-to-ground link of the liaison system is different from that of the ground-to-air link. This is a result of the fact that the contribution of noise generated within the receiver to the output noise power is negligible in comparison to the contribution of atmospheric noise; in the h-f frequency band it is almost always the atmospheric noise picked up by the receiving antenna which determines the noise level in the receiver output. Nevertheless it was possible to evaluate the antennas for use in both links with data obtained from the ground-to-air link alone.

Briefly, the evaluation flight tests were conducted as follows:

(1) A distant station transmitted a modulated signal at the predicted frequency for optimum transmission over the path to the aircraft. The modulation level and the power level at the transmitter were kept constant during the test. The modulation consisted of two audio tones at the same voltage level, one at 559 cps and one at 2,000 cps.

(2) The aircraft was flown in a test pattern consisting of four interlaced hexagons so that twenty four courses correponding to each 15 degrees of azimuth were traversed (Fig. F-1).

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* Prepared by John Taylor.

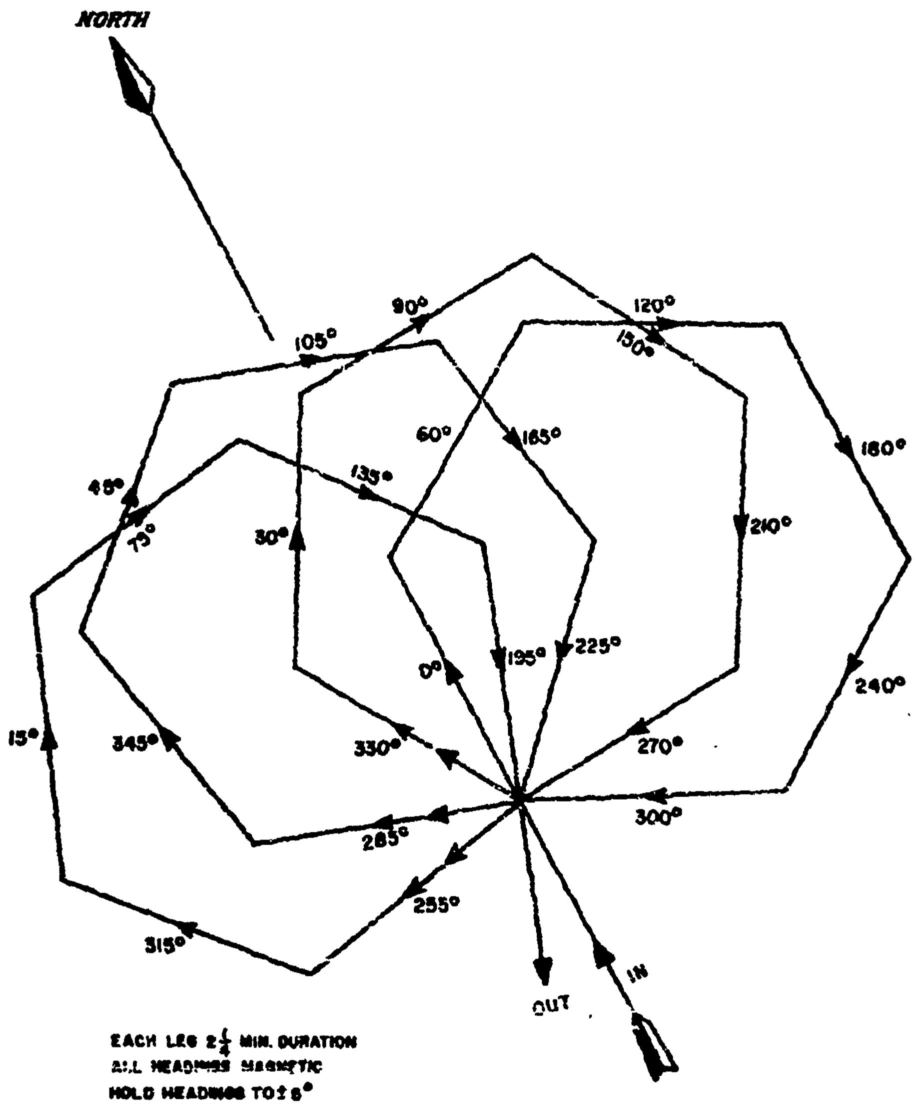

FIG. F-1

FLIGHT PATTERN

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(3) A receiver on the aircraft was tuned to the frequency of the transmitted signal. For 2¼ min on each course the audio output of the receiver was recorded on tape while the receiver was switched from one antenna to another every 15 seconds. A superimposed audio tone above the pass band of the receiver designated which antenna was being used.

(4) The recordings of the receiver output were analyzed to obtain distributions of received signal power or distributions of signal-to-noise power, as described in Appendix G.

Most of the flight tests were conducted with the aircraft in the vicinity of San Francisco and with the transmitting station located at Wright-Patterson Air Force Base, near Dayton, Ohio. To obtain a more varied set of test conditions, the terrain over which the aircraft maneuvered was varied by changing the exact location of the test. The frequency of transmission was always the first assigned frequency below the optimum predicted frequency for the transmission path; many different frequencies were used, however, since tests were conducted at different times of day and over a period of several months.

One series of tests was conducted with the aircraft in the vicinity of San Antonio, Texas. Two transmission paths were used during this series, one with the transmitter at Wright-Patterson Air Force Base and the other with the transmitter at Palo Alto, California.

B. THE RELATIONSHIP BETWEEN THE AIRBORNE TRANSMITTING SYSTEM AND THE AIRBORNE RECEIVING SYSTEM

If the antennas are to be evaluated for use with a receiving system, the recordings need be analyzed for signal-to-noise power distributions only. In this case it is not necessary to match the antennas or the receiver to the transmission line. It is essential, however, that the mismatch losses are not so great that noise generated within the receiver itself becomes an appreciable fraction of the noise in the output of the receiver. The receiver may be operated with AVC since the signal-to-noise ratio is established at the receiver input.

When the antennas are to be evaluated for use with a transmitting system, the evaluation should be based on the distributions of signal-to-noise power at the ground receiver. Since it is more convenient to record the signal received at the aircraft, it is necessary to consider the relation between the signal received on the ground and that received at the aircraft. In the first place, the intensity of the noise field at the aircraft is not related to the intensity of the noise field at the distant ground station. Moreover, the intensity of noise at the airborne receiver is a function of the gain of the airborne antenna, and although it has been shown (Appendix D) that the noise is spread over such a wide azimuthal sector that it is relatively independent of the heading of the aircraft,

it does depend on the average gain in a small vertical sector near the horizon. It is therefore apparent that signal-to-noise ratios at the aircraft cannot be used for an evaluation of the airborne transmitting system. However, the noise distributions at the aircraft and at the ground station have one characteristic in common — the standard deviation of the noise power from its mean value is small compared to the standard deviation of the signal power received from a distant transmitter. The last statement is equivalent to saying that the shape of the signal-to-noise distribution curves and the shape of the signal strength distribution curves are almost identical. Since the mean value of the noise at the ground station remains constant during the interval of time required to fly a hexagonal pattern, the relative merit of the antennas can be obtained from the distributions of signal power at the ground receiver rather than from the signal-to-noise distributions. There are no non-linear elements between the terminals of the transmitting antenna and the terminals of the receiving antenna; consequently the reciprocity theorem can be applied and it is at once evident that the signal strength distributions must be the same whether the receiver is in the aircraft or at the ground station. Therefore, when the distributions of signal power received on the aircraft are known, the antennas can be evaluated for use with an airborne transmitter.

To obtain the distributions of received signal strength the receiver must be operated without AVC and must be used only in its linear range. In addition, the ratio of power received to maximum power obtainable from the antenna must be known for each antenna so that the basis for comparison can be made the same in all cases. The basis chosen was the lossless, matched condition.

The ratio of received power to the maximum power available from the antenna is directly proportional to the power transfer efficiency of the matching network between the antenna and the transmission line, and the effectiveness of the match at the antenna terminals. Although the power transfer efficiency of this matching network is not the same in transferring power from the transmitter to antenna as it is for power flow in the reverse direction, it can be shown that the ratio of received power to power available from the antenna is equal to the ratio of transmitted power to power available from the transmitter if the output impedance of the transmitter is equal to the input impedance of the receiver. To show this, let the ratio of received power to power available from the antenna

be E_r and the ratio of transmitted power to power available from the transmitter be E_t. Then

$$E_t = \frac{P_t}{P_{t_{max}}} = \frac{4R_t R_1}{|Z_t + Z_1|^2} \eta_t, \tag{F-1}$$

and

$$E_r = \frac{P_r}{P_{r_{max}}} = \frac{4R_a R_2}{|Z_a + Z_2|^2} \eta_r, \tag{F-2}$$

where

P_t is the transmitted power

$P_{t_{max}}$ is the maximum power available from the transmitter (power into a matched load)

P_r is the received power

$P_{r_{max}}$ is the maximum power available from the antenna

$Z_t = R_t + jX_t$ is the output impedance of the transmitter

$Z_r = R_r + jX_r$ is the input impedance of the receiver

$Z_a = R_a + jX_a$ is the input impedance of the antenna

$Z_1 = R_1 + jX_1$ is the input impedance of the transmission line at the transmitter (or receiver terminal) with the matching unit and antenna connected

$Z_2 = R_2 + jX_2$ is the input impedance of the transmission line at the antenna with the same matching unit and the receiver connected

η_t = power transfer efficiency of the matching network in the transmitting case

η_r = power transfer efficiency of the same matching network in the receiving case

From the definitions of E_t and E_r as given by Eqs. (F-1) and (F-2):

$$E_t = \frac{4|I_a|^2 R_a R_t}{V_t^2}, \tag{F-3}$$

and

$$E_r = \frac{4|I_r|^2 R_r R_a}{V_r^2}, \tag{F-4}$$

Where

V_t is the open circuit voltage at the transmitter, assuming a constant voltage generator

I_a is the current at the antenna terminals, due to V_t

V_r is the open circuit voltage at the antenna

I_r is the current in the receiver terminals to the voltage V_r

Since it is assumed that $Z_t = Z_r$, then from the reciprocity theorem

$$\frac{I_r}{V_r} = \frac{I_a}{V_t},$$

and therefore

$$E_r = E_t$$

It should be noted again that η_r is not, in general, equal to η_t.

C. GROUND STATION

During each flight test a ground station several thousand miles away from the aircraft transmitted a signal at constant power level and with constant modulation. The frequency of transmission was selected to be as near the computed optimum for the path as possible with assigned frequencies approximately 2 Mc apart. The next assigned frequency below the computed optimum was always used except in cases where interference from other stations was very strong.

The transmitted signal consisted of an r-f carrier modulated with two audio tones, one at 2000 ±5 cps and the other at 559 ±2 cps. It was thought that several tones would represent speech modulation much better than a single tone, particularly if selective fading were present over the link. With several tones the fading of one of the sidebands would have a comparatively minor effect on the total modulation power in the received signal. It was not feasible to use more than two tones, however, since the signal was separated from the noise in the analyzer by means of narrow band filters; if more than two tones had been used, more of the noise would have been introduced into the signal channel and the minimum measurable signal-to-noise ratio would have increased.

D. FLIGHT PATTERN

Since the r-f carrier level and the percentage modulation at the transmitter were kept constant during each test flight, the received signal strength was a function of the antenna pattern and the ionospheric transmission path, only. As it was desired to evaluate the antennas in the presence of the fading caused by random short term fluctuations (2 to 50 sec) in the ionosphere, it was necessary to keep the aircraft on a particular heading long enough to obtain a representative sample of the signal received on each antenna. However, when enough different headings are flown to represent adequately the entire azimuthal pattern, the time consumed is so long that the overall character of the fading changes with the diurnal variations of the ionosphere. The flight pattern consisting of four interlaced hexagons (Fig. F-1) was a practical solution to this dilemma. Holding each course for 2½ min is long enough to obtain a representative sample of the fading signal and noise on the three antennas at one point in the pattern, yet changes in overall propagation conditions are usually negligible during the 15 min required to traverse a hexagon. Although the six points sampled on a single hexagon are not enough for evaluating the antenna, they are uniformly distributed in azimuth and form a representative sample. The data from the four hexagons form four such samples which together represent the whole azimuthal pattern quite well. These four samples were not obtained for the same fading conditions, since the propagation conditions change appreciably during the period of an hour, but since each individually is a representative sample, it is permissible to average the results in the evaluation scheme (Chap. VII).

E. ANTENNAS

The airborne antennas compared (Fig. F-2) were an isolated tail cap, an isolated wing cap, and a fixed wire. The tail-cap antenna (Fig. F-3) consisted of the top 7.5 ft of the vertical stabilizer and was isolated by a Fiberglas section 7.5 in. in width. The driving point was across the gap formed by the Fiberglas section, and the antenna matching unit (Fig F-4) was mounted just below this gap. The wing-cap antenna (Fig. F-5) was similar in construction to the tail cap; it consisted of a 44.7 in. section of the wing tip, isolated by 31 in. of Fiberglas, and was driven across the center of this gap. Again, the matching unit was adjacent to the gap. The Fiberglas material in both of the cap-type

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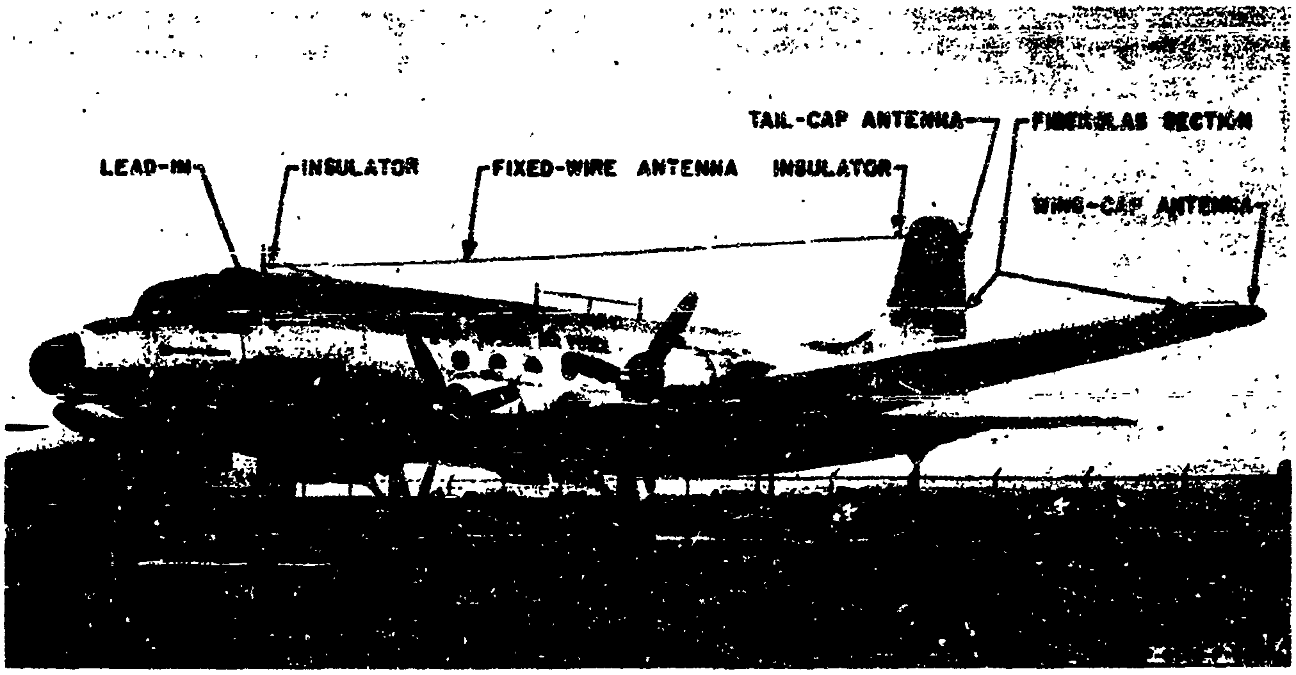

FIG. F-2
C-54 AIRCRAFT FOR TESTING LIAISON ANTENNAS

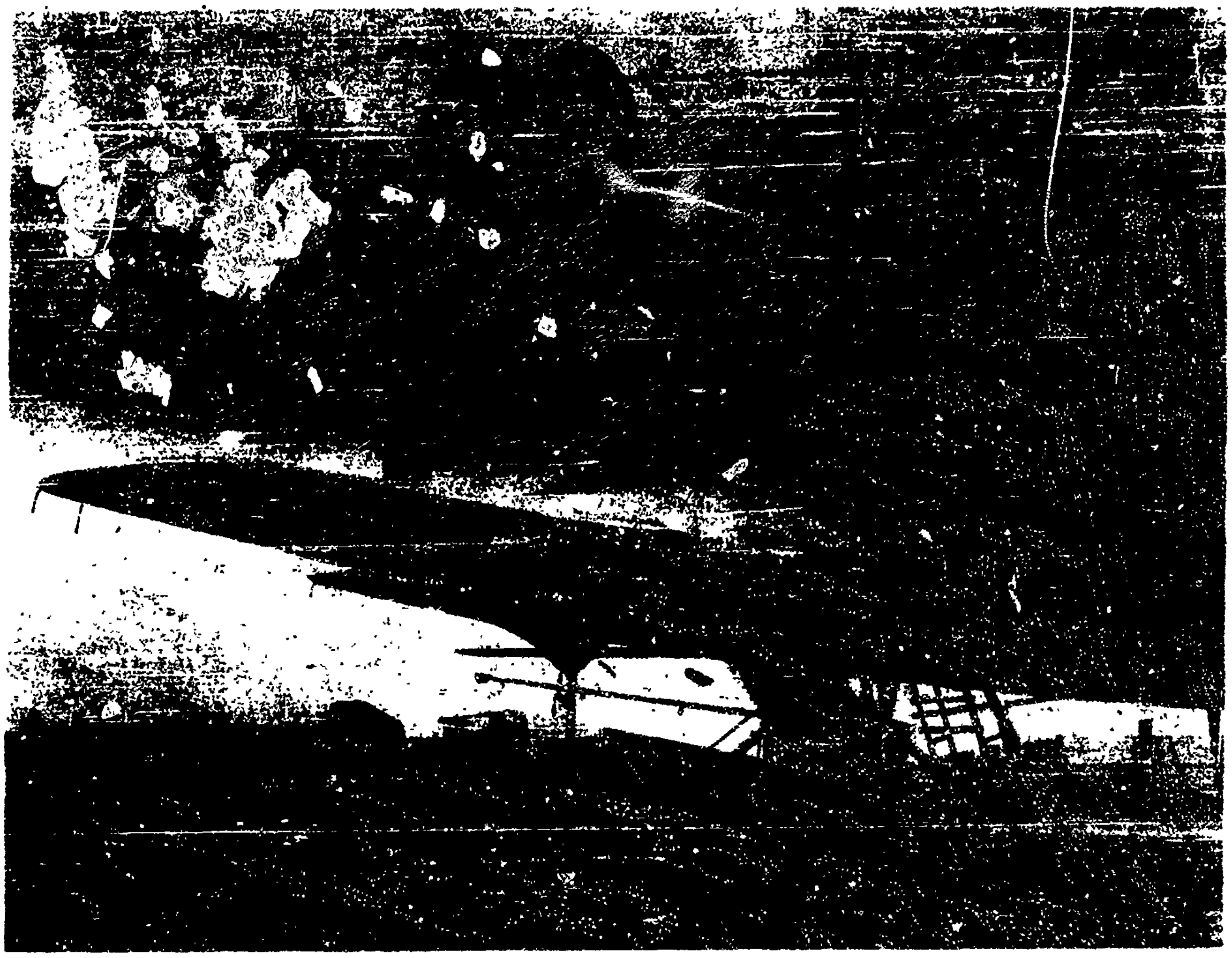

FIG. F-3
TAIL-CAP ANTENNA

FIG. F-4

TAIL-CAP ANTENNA AND MATCHING UNIT

FIG. F-5

WING-CAP ANTENNA AND MATCHING UNIT

FIG. F-5

WING-CAP ANTENNA AND MATCHING UNIT

antennas was somewhat lossy and had a tendency to absorb moisture. The lossiness of this material continued to increase during the whole time that the aircraft was based at Oakland Airport.

The fixed-wire antenna was a straight section of No. 20 polyethylene covered wire, 60 ft in length, stretched along the center line of the aircraft from the top of the vertical fin to a point 14 ft from the nose; the antenna was insulated at the fin and the lead-in was at the forward end. The matching unit (Fig F-6) was inside the fuselage.

Both the wing cap and tail cap were provided with a relay which placed a short circuit across the driving gap when the antenna was not in use. Thus, an antenna which was not in use was effectively removed from the airframe and could have no effect on the performance of the antenna being tested. The fixed-wire antenna could not be made to disappear so easily, however, since this conductor would not ordinarily be present on aircraft which use cap-type antennas. To minimize the effect of the fixed wire, a relay which could be made either to open the circuit between the antenna and the matching unit or to ground the antenna to the airframe was placed in the lead-in. When the fixed wire was not being used the relay was switched to the position which most effectively broke up the resonance in the antenna structure.

In order to be able to use the recorded data from the flight tests to obtain both signal-to-noise distributions and distributions of received signal strength, each antenna was matched, by means of a matching network at the antenna terminals, to the 50-ohm transmission line so that the VSWR was less than 3:1. Although the receiver was designed to work with a 300-ohm antenna, the match was sufficiently good to insure that noise picked up on the antenna was the dominant source of receiver output noise; this was the only requirement for the signal-to-noise distributions. The receiver was used without AVC, and E_r was measured for each antenna; thus the requirements for obtaining signal strength distributions were also satisfied.

It was shown above that $E_r = E_t$ when $Z_r = Z_t$. Since it is much more convenient to measure η_t than it is to measure η_r, η_t was measured for the matching unit and transmission line by the method given in Appendix A, para 4.4.5.2.2. The impedance, Z_1, at the receiver terminals of the transmission line with the matching unit and antenna connected

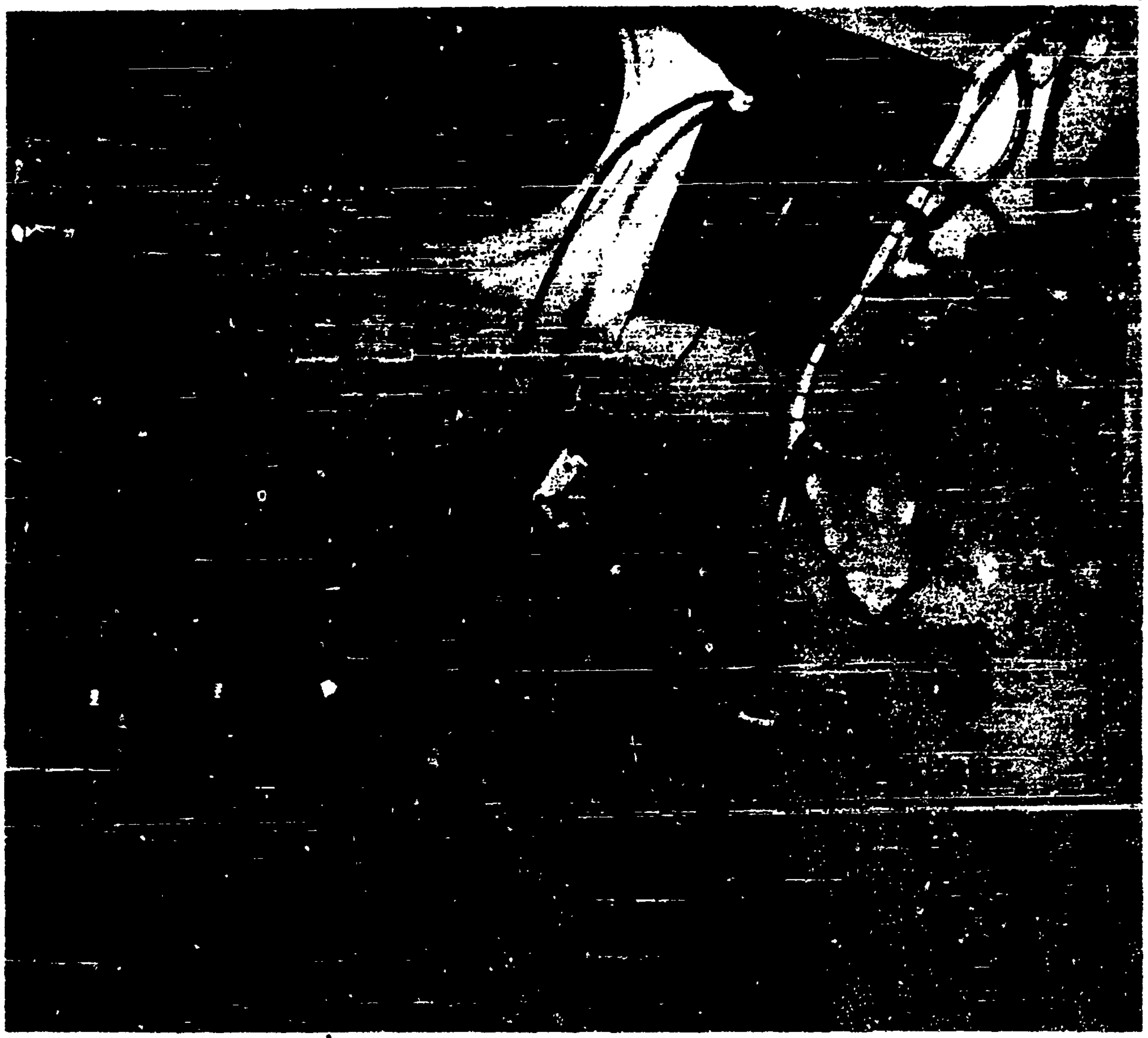

FIG. F-6
MATCHING UNIT FOR FIXED-WIRE ANTENNA

was measured in flight, and E_t was computed from Eq. (F-1) with Z_r substituted for Z_t. The data was then corrected to correspond to the perfectly matched lossless case and the antennas were compared on this basis.

F. FLIGHT TEST EQUIPMENT

Figure F-7 is a block diagram of the airborne equipment used for obtaining signal strength data from the three antennas, in the form of recordings on magnetic tape. The matching units for both the wing-cap and tail-cap antennas were near the driving gaps of the antennas but could be remotely tuned from control units in the cabin; the matching unit for the fixed wire was in the forward part of the cabin and was readily accessible for adjustment during flight, as was the rest of the test equipment which was located in the main cabin (Figs. F-8 and F-9).

RG-8/U coaxial cable led from each of the matching units to a coaxial switch (Fig. F-10) which cyclically connected each antenna in turn to the receiver. This switch was motor driven and the switching time was about ½ sec. A second motor driven switch was used to control the cycling of the antenna switch and was adjusted so that one antenna was connected to the receiver for approximately 15 secs. This timing or cycling switch also controlled the relays which short circuited the unused antennas; in addition it switched the frequency of the identification oscillator so that a particular tone was always recorded when a given antenna was connected.

The airborne receiver for the flight tests was a Collins type 51-J. The i-f bandwidth of this receiver was increased so the overall result was a bandwidth from 300 to 3500 cps as far as the modulation was concerned. This is about optimum for speech intelligibility.

The audio output of the receiver was mixed with the identification tone and the marker tone in a simple resistive pad used as a mixer circuit. The output from the mixer was recorded on magnetic tape in an Ampex type 400 recorder. In order to keep the recorded signal tones within the tolerances required by the signal analysis equipment, a tuning fork oscillator was used to furnish the 60-cps power for the synchronous drive motor in the recorder.

The identification tone for each of the antennas was generated by a simple audio oscillator this tone, which was above the passband of the

receiver, was separated from the recorded signal and noise by filters in the signal analysis equipment and was used to identify the antenna under test. A 60 cps marker tone was recorded for two seconds at the start and end of each leg of the hexagon. The marker tone, which was below the pass band of the receiver, was used to start and stop the counters in the signal analysis equipment.

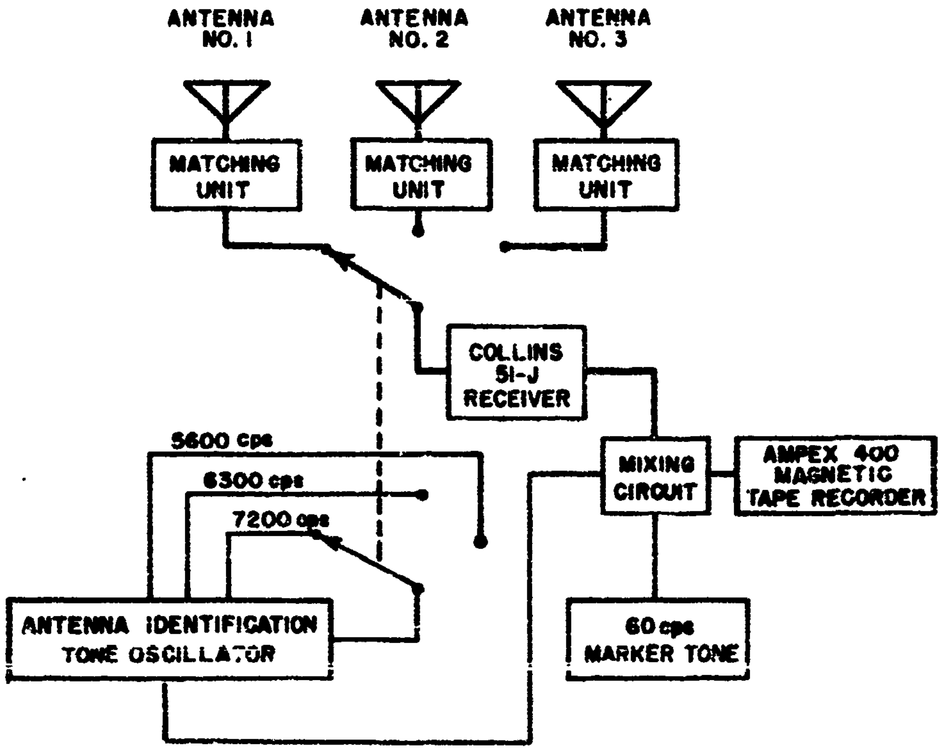

FIG. F-7

BLOCK DIAGRAM OF AIRBORNE EQUIPMENT FOR OBTAINING SIGNAL POWER DATA

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FIG. F-8
INSIDE VIEW OF MAIN CABIN OF C-54 AIRCRAFT SHOWING TEST EQUIPMENT

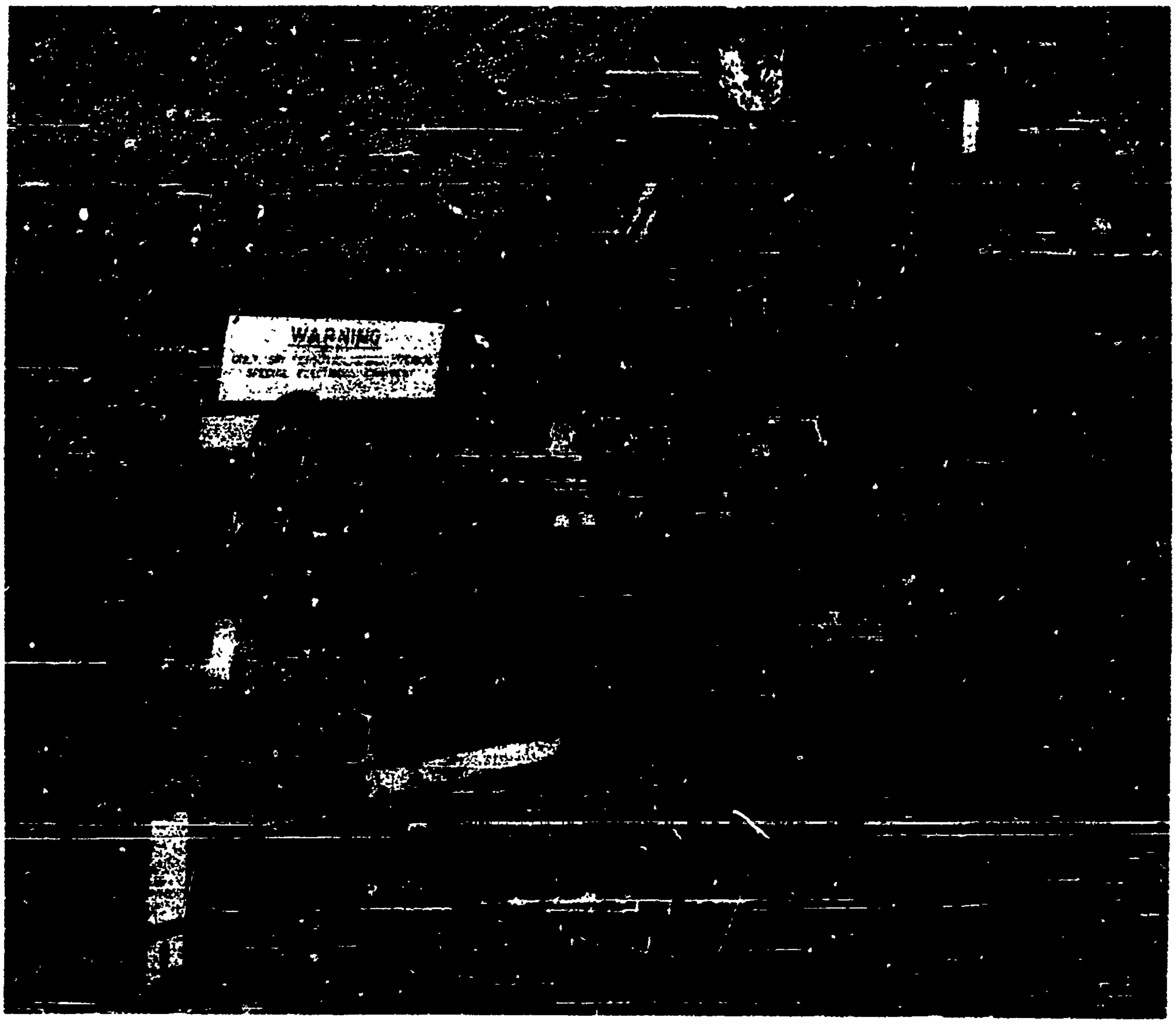

FIG. F-9

INSIDE VIEW OF CABIN SHOWING REMOTE CONTROL UNITS FOR ANTENNA MATCHING CIRCUITS

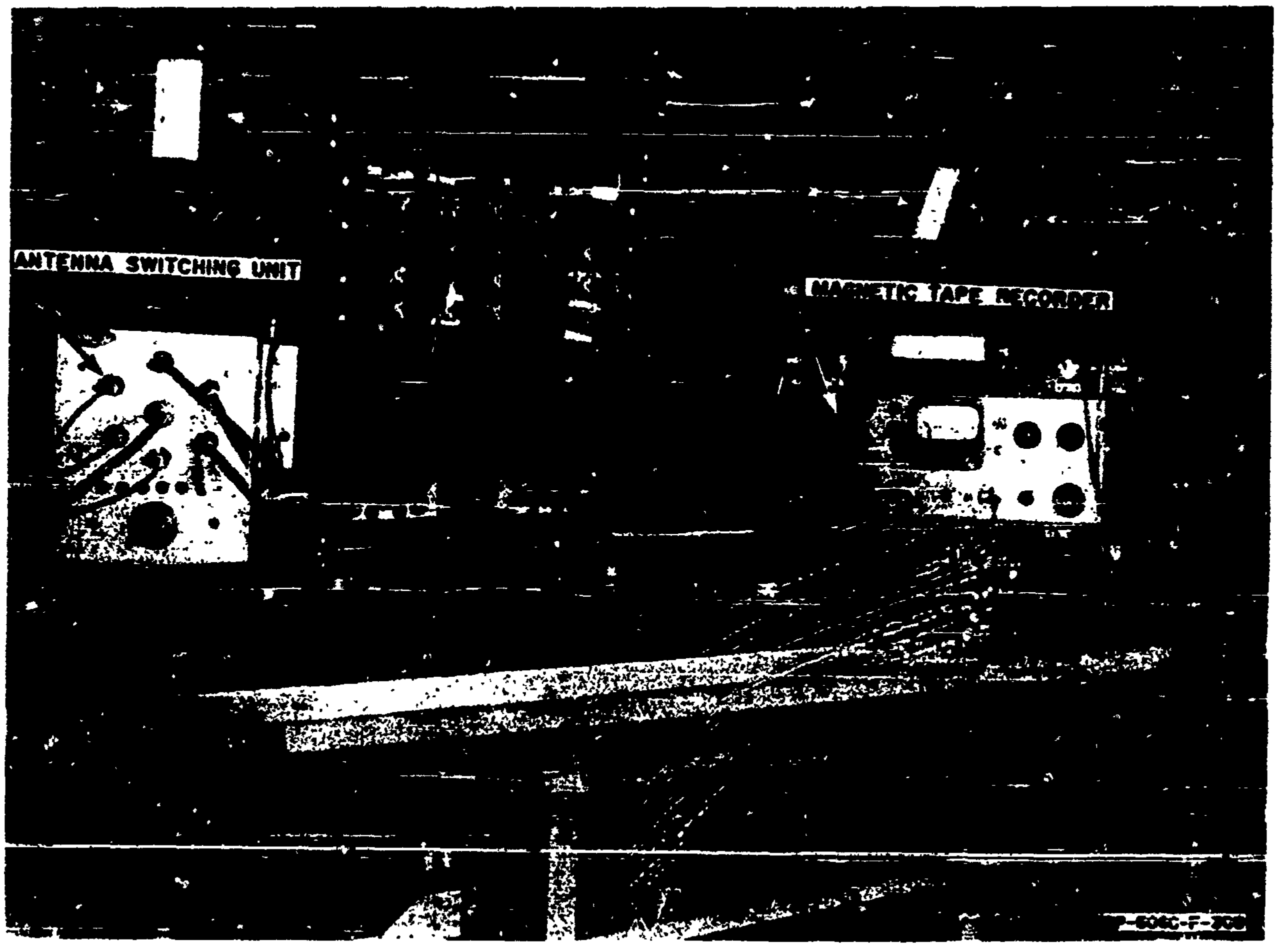

FIG. F-10

INSIDE VIEW OF CABIN SHOWING ANTENNA SWITCH AND TAPE RECORDER

APPENDIX G

EQUIPMENT FOR MEASURING SIGNAL-TO-NOISE RATIO DISTRIBUTIONS*

A. INTRODUCTION

This appendix is a description of the equipment used for analyzing the received signal and noise data recorded on magnetic tape, in order to obtain distributions of signal-to-noise power ratios. The equipment can also be used to obtain distributions of signal power, or distributions of noise power, alone.

Before describing the equipment, however, it is necessary to define the quantities "signal power" and "noise power," which the apparatus is to measure and compare. The signal in which we are interested consists of one or two audio tones which independently increase and decrease in amplitude at a rate which is slow compared to the tone frequencies. For a single tone the signal power is defined as the average power in a narrow frequency band, Δf, centered about the tone frequency, the average being taken during an interval of time Δt. Since the interval Δt is independent of the period of the tone, it is evident that this interval must be long compared to the tone period to insure that the average power does not vary as the second harmonic of the tone. Moreover, since it is desired to obtain a distribution of signal power to show the variation of signal strength caused by fading, it is necessary to choose an interval, Δt, which is short compared to the average fading period during the test. The width of the frequency band, Δf, is relatively unimportant since it is impractical to obtain a bandwidth smaller than the extremely narrow band of frequencies in which the signal power is concentrated; Δf must, however, be small enough so that the noise power contained in it is negligible in comparison to the signal power, and in addition it must be large enough to accommodate the frequency drift of the audio tone. When more than one tone is used, the signal power is defined as the sum of the

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* Prepared by John Taylor.

powers in the bands, Δf_1, Δf_2 . , centered around the tone frequencies f_1, f_2 $\cdots$.

In a similar manner, the noise power is defined as the average power in the whole audio band being used, exclusive of the narrow bands, Δf_1, Δf_2 . , in which the signal power is concentrated. As before, the average must be taken over an interval of time Δt, and when signal and noise powers are to be compared, the interval must be the same for both the signal and the noise. An interval appropriate for the signal is also appropriate for the noise, since the fading rates are of the same order of magnitude, and the lowest signal frequency and lowest frequency component in the noise are of the same order of magnitude.

There is one other consideration in the choice of the time interval Δt, which is a result of the use to which the distributions will be put. The distributions of signal-to-noise power will be used to determine articulation scores and hence the intelligibility of voice communication over the link from which the signal and noise data was recorded. The intelligibility of each syllable is dependent on the average signal-to-noise ratio during the interval of the syllable; this is the basis for using signal-to-noise ratio distributions for computing articulation scores. Therefore, the interval during which the signal and noise powers are averaged should be of the order of a syllable length This requirement, together with the requirement that the interval be long compared to the period of the lowest frequency component yet short compared to the average period of fading, will be satisfied if Δt is between $1/6$ and $1/20$ sec.

The signal and noise data to be analyzed were recorded on magnetic tape as described in Appendix F. The signal consisted of two audio tones with frequencies of 559 cps and 2000 cps, respectively. Since the recorded signal came from the output of a receiver in an h-f communication link, the noise was predominantly of atmospheric origin, and the signal was subject to fading which is characteristic of ionospheric propagation. In addition to the signal and noise data, several tones, outside the range of frequencies passed by the receiver, were recorded to identify the antenna under test and to indicate when the aircraft was on the desired heading.

In the analysis of the signal and noise data, the signal was separated from the noise by narrow band filters and both the signal and the noise were fed into special circuits, the d-c outputs of which were proportional to the mean square of the input voltages for an interval of the

order of $\Delta t = 1/10$ sec. The output of the signal channel was then compared with the output of the noise channel in a differential amplifier; and a constant speed counter, switched on whenever the signal exceeded the noise, measured the time during which the signal-to-noise ratio was greater than a given value. The value of the signal-to-noise ratio at which the counter was switched was controlled by a calibrated attenuator in the signal channel. The distribution of signal-to-noise ratios was obtained by measuring the time that the signal output exceeded the noise output for several settings of the attenuator.

B. DESCRIPTION OF EQUIPMENT

A block diagram of the equipment is shown in Fig. G-1. The audio output of the tape recorder playback is fed into two channels. One channel comprises the main part of the equipment in which the signal analysis is

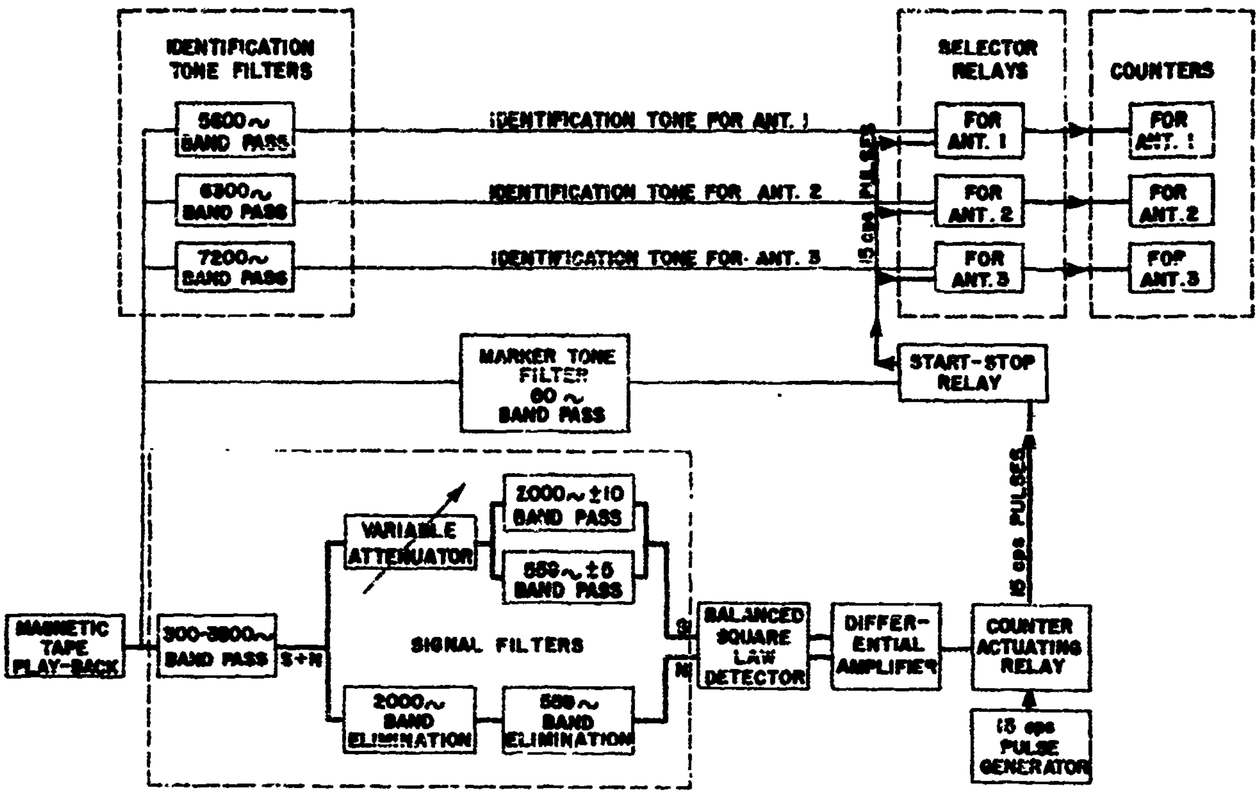

FIG. G-1

BLOCK DIAGRAM OF EQUIPMENT FOR MEASURING DISTRIBUTIONS OF SIGNAL-TO-NOISE POWER RATIOS

actually accomplished. The other channel is an auxiliary part of the equipment in which the identification tones are separated by filters and used to select the desired counter, and to start and stop the equipment so that data taken only on predetermined headings of the aircraft are analyzed.

In the main channel, only those frequencies in the range from 300 to 3500 cps — the pass band of the receiver — are accepted; the characteristics of the 300-3500 cps filter are shown in Fig. G-2 (note that the ordinate scale is proportional to power, not voltage). Immediately following the band pass filter are two filter channels in parallel which separate the frequency band into two complementary parts. One part consists of the whole band with the exception of two narrow slots centered at 559 and 2000 cps respectively; this channel passes the noise but rejects the signal. The other part consists of the two narrow bands at 559 and 2000 cps; in this case only the signal is passed.

Each of the two band elimination filters in the noise channel consists of one constant-k section with a cathode follower stage at the input. The two sections are connected in cascade and there is a triode amplifier at the output of the second filter. The characteristics of these two filters are shown in Fig. G-3.

Each of the two filters in the tone-signal channel consists of a two stage amplifier with a double-tuned circuit in the output of each stage. The d-c plate current is carried by a resistor in the plate circuit and the gain is purposely kept low, while maintaining a narrow bandwidth, by inserting a 0.5-megohm resistor in series with the coupling condenser between the plate and the tuned circuit. The grid of the input stage of each of these amplifiers is connected to a common input terminal; a stepped attenuator ahead of this terminal is used to change the ratio of the gains in the signal and noise channels to permit the distribution of signal-to-noise ratios to be measured. The gain of each amplifier can be varied independently of the other by a potentiometer between the two stages; this permits the gain in each of the tone channels to be made equal to the average gain in the noise channel when the stepped attenuator is set on 0 db. The output of each of these amplifiers is connected to the input grid of a common triode amplifier stage. The frequency response of each of these amplifiers is shown in Fig. G-3.

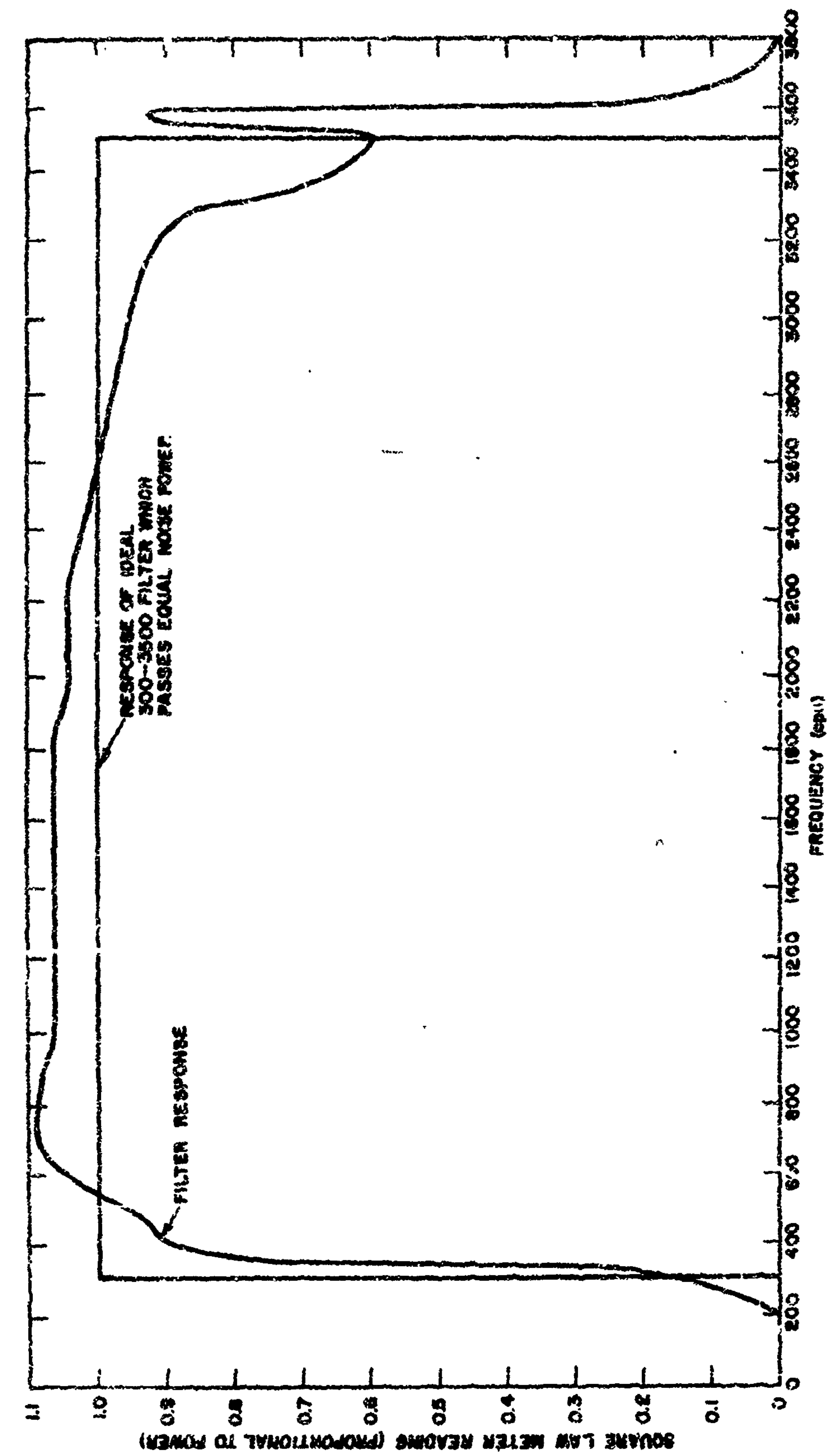

FIG. G-2

FREQUENCY RESPONSE OF 300–3500 CPS BAND-PASS FILTER

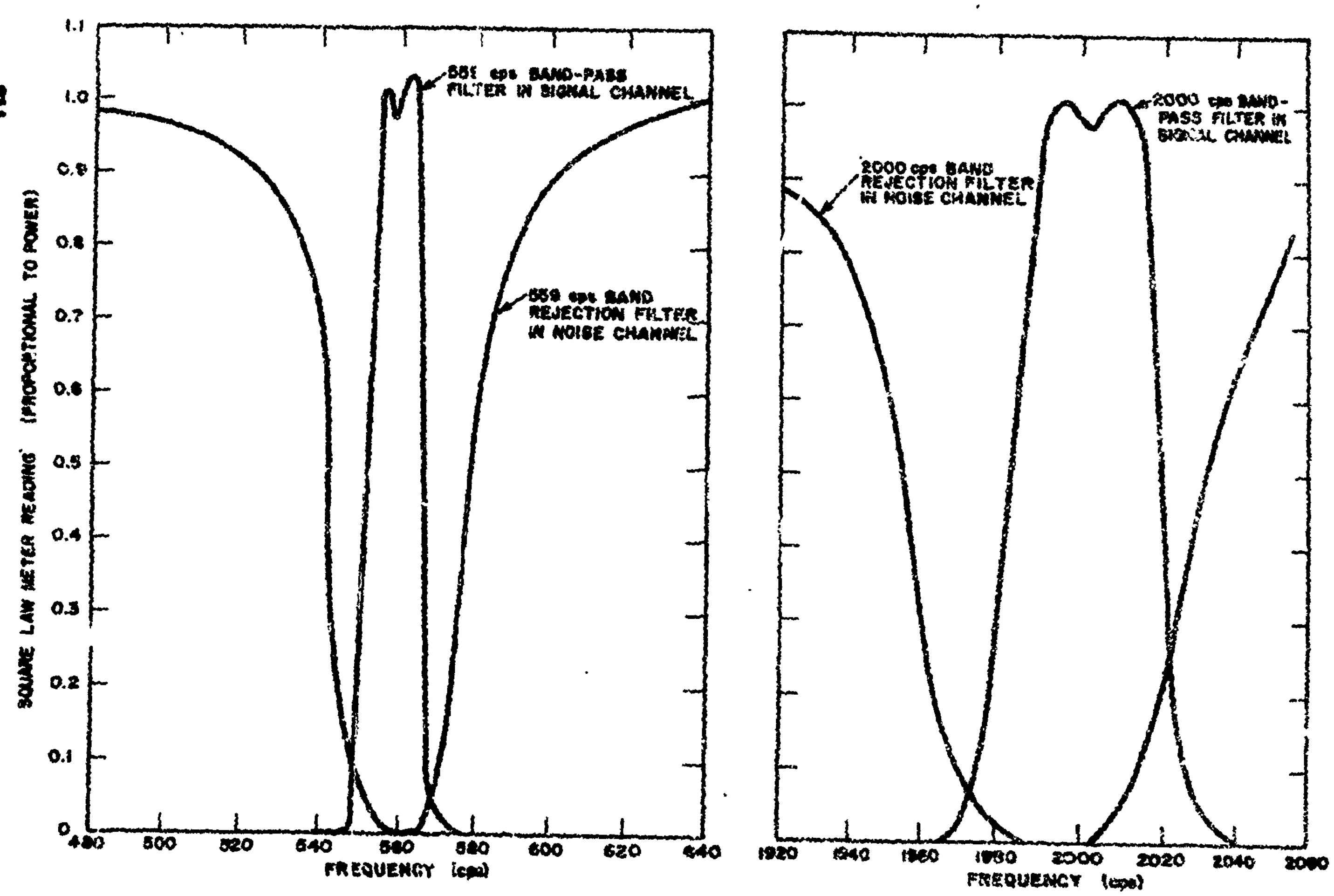

FIG. G-3
FREQUENCY RESPONSE OF 559 CPS AND 2000 CPS BANDPASS AND BAND REJECTION FILTERS

Following the filter circuits in the main channel is a square-law meter with dual metering circuits, one for the noise and one for the tone-signal. These two metering circuits are identical and the d-c output voltage from each is proportional to the mean square of the instantaneous input for an interval of time, Δt; any of several values of Δt in the range 0.01-0.125 secs can be selected. Aside from its use here, this mean-square voltmeter is of general interest. Since the circuit is not conventional, it is described in detail in Sec. C of this appendix.

The two d-c output voltages from the square-law meter, one proportional to the noise power and the other proportional to the signal power, are compared in a differential amplifier; when the signal power is greater than the noise power a relay in the counting circuit is closed permitting one of the counters to count at the rate of fifteen counts per second.

The counting circuit is quite simple; it consists of a 6 volt a-c transformer connected in series through a pair of contacts driven at 15 cps by a synchronous motor, and through several relay contacts to three electromechanical counters in parallel. When all of the relays in series with a particular counter are closed, the counter counts the 15-cps pulses generated by the motor driven contacts. One of the relays is controlled by the output of the differential amplifier in the main channel as described above; the other relays are actuated by the outputs from the auxiliary channel and serve to connect the counter for a given antenna only, when the signal from that antenna is being played back.

The auxiliary channel consists of four band-pass filters, one for each of the identification tones and one for the 60 cps marker tone which marks the start and stop of each leg of the hexagonal flight pattern. The output of each of the indentification filters is amplified and fed into the grid of a thyratron biased so that the tube does not normally conduct; the plate current for each of the thyratrons flows through the field coil of a relay. When a particular tone is present, the thyratron which that tone fires closes the relay to the counter associated with the tone; whenever the tone is present this counter is connected in the counter circuit. Thus, by means of the identification tone, the data from a given antenna are always recorded on the same counter.

The 60-cps marker tone is fed into a relay circuit arranged so that one pulse (2 sec duration) of tone closes a relay in series with the counter pulses and the next one opens it; if the relay is open, it remains

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The 60-cps marker tone is fed into a relay circuit arranged so that one pulse (2 sec duration) of tone closes a relay in series with the counter pulses and the next one opens it; if the relay is open, it remains

open until a marker pulse is received, and if it is closed it remains closed until a marker pulse appears. The marker pulses, which are recorded at the beginning and end of each leg of the hexagonal flight pattern, thus close the circuit to the counters during the intervals of test while the plane is flying on the chosen headings and open it during the intervals while the plane is changing course.

Although this equipment was designed to measure distributions of signal-to-noise power ratios, it can be used to measure distribution of signal power or distributions of noise power alone. To measure distributions of signal power the noise channel is disconnected at the input to the square-law meter and a constant a-c voltage from a signal generator is connected in place of the noise. The tone signal is thus compared to a constant, and distributions of signal power are obtained. A photograph of the equipment is shown in Fig. G-4

C. MEAN-SQUARE VOLTMETER CIRCUIT

The square-law meters employed in the equipment make use of a technique described by Tanner,[1] for obtaining stabilized non-linear transfer characteristics. The basic squaring circuit is shown in Fig. G-5.

The Thyrite resistors in the cathodes of the 6SLT triodes provide a nonlinear feedback voltage which is dependent on the tube plate current. The effect of this feedback is to give the stages transfer characteristics described by the power series of Eq. (G-1).

$$i_a = a_1 e_i + a_2 e_i^2 + a_3 e_i^3 + \dots \qquad \text{(G-1a)}$$

$$i_b = a_1(-e_i) + a_2(-e_i)^2 + a_3(-e_i)^3 + \dots \qquad \text{(G-1b)}$$

The second order coefficients, a_2, shown in the equations are relatively large, and depend chiefly on the characteristics of the Thyrite elements rather than on the tube, and are hence relatively stable.

When the currents i_a and i_b are added in the output as shown in the figure, we arrive at the expression

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[1] R. L. Tanner, "Stabilized Non-Linear Transfer Characteristics by Means of Feedback from Non-Linear Elements," paper presented at West Coast I.R.E. Convention; September 1950.

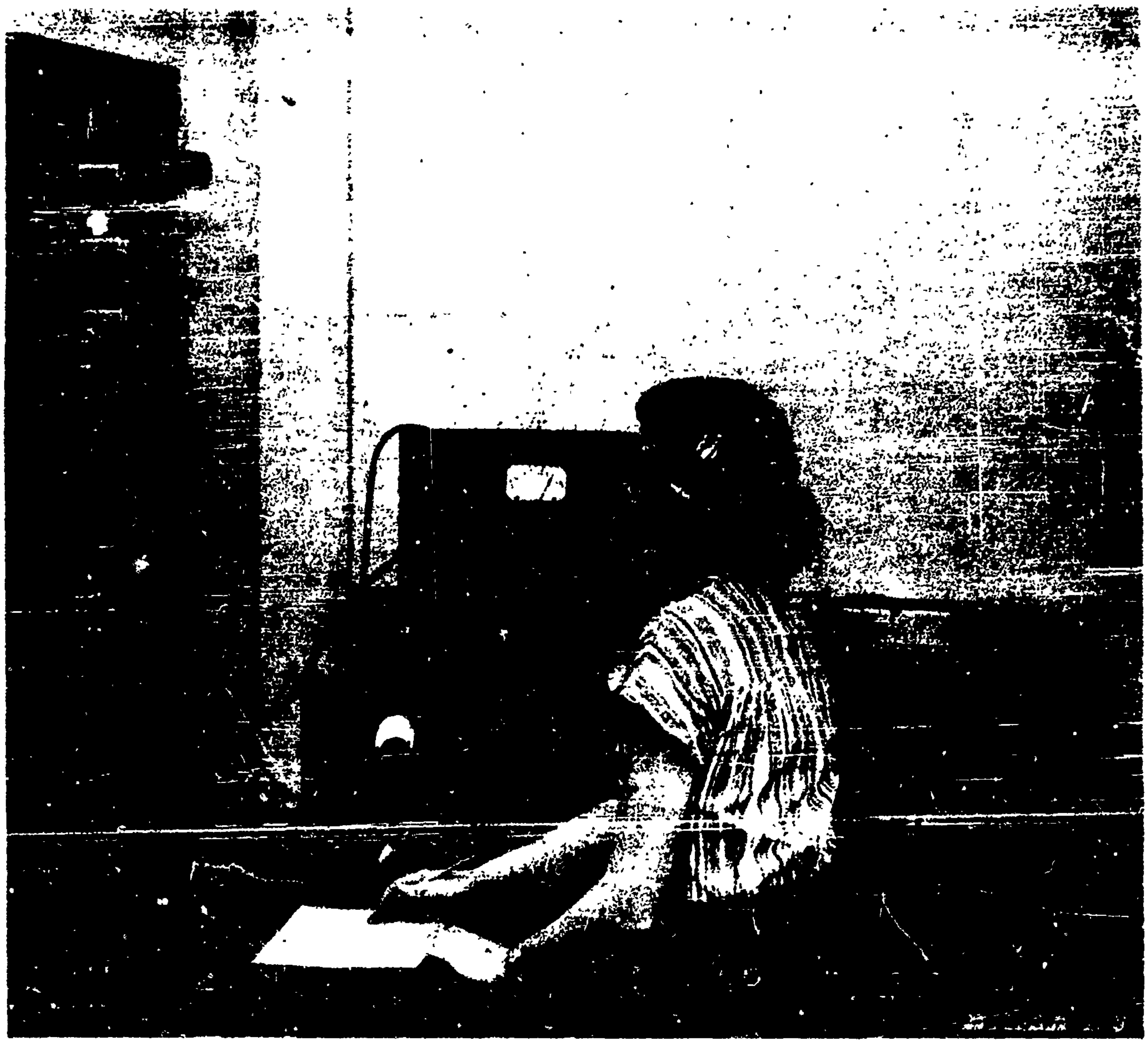

FIG. G-4

EQUIPMENT FOR MEASURING DISTRIBUTIONS OF SIGNAL-TO-NOISE POWER RATIOS

$$i_0 = i_a + i_b = 2(a_2 e_i^2 + a_4 e_i^4 + \dots) \, . \tag{G-2}$$

As shown in Eq. (G-2) the odd order terms cancel when the currents i_a and i_b are added. Furthermore, the characteristics of the Thyrite are such that even order coefficients higher than the second are extremely small compared to a_2, and can be neglected for current values which do not exceed the useful operating range. The transfer characteristic of the entire circuit is therefore, effectively:

$$e_0 = R_L i_0 \cong 2a_2 R_L e_i^2 \, . \tag{G-3}$$

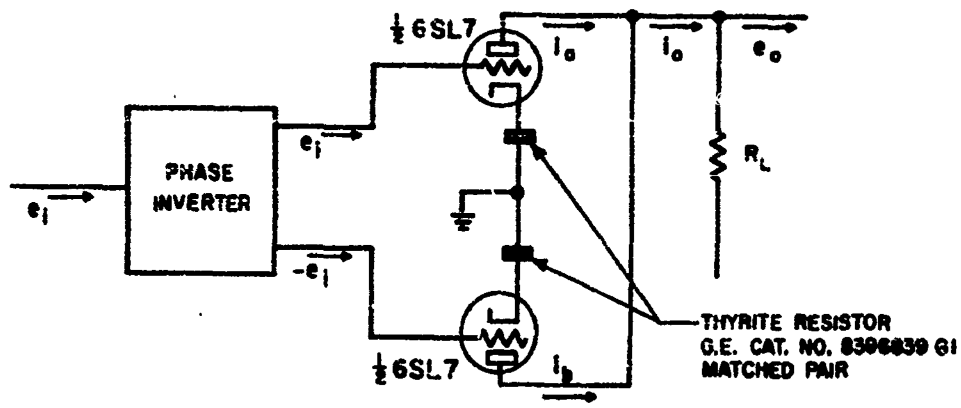

FIG. G-5
SQUARING CIRCUIT

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Thus, we have a device with a transfer characteristic such that the instantaneous output voltage is proportional to the square of the instantaneous input voltage. To make a mean-square reading device it is only necessary to filter the output voltage with a resistance-capacitance filter which averages the instantaneous output over an appropriate time interval.

Figure G-6 is a diagram of the complete circuit of the square-law meter used in the equipment and Fig. G-7 is a graph showing the performance of this meter. It can be seen from the curves in Fig. G-7 that the circuits operate with negligible error over a range of output voltages of 100 to 1. Other devices employing the same principles have been found to

operate well over a range of 10 to 1. The curves as drawn show a slight displacement between the responses of the two channels This displacement was introduced in order to better show the individual characteristics of the channels. It could be corrected, of course, by a slight adjustment of the relative gain settings of the channels.

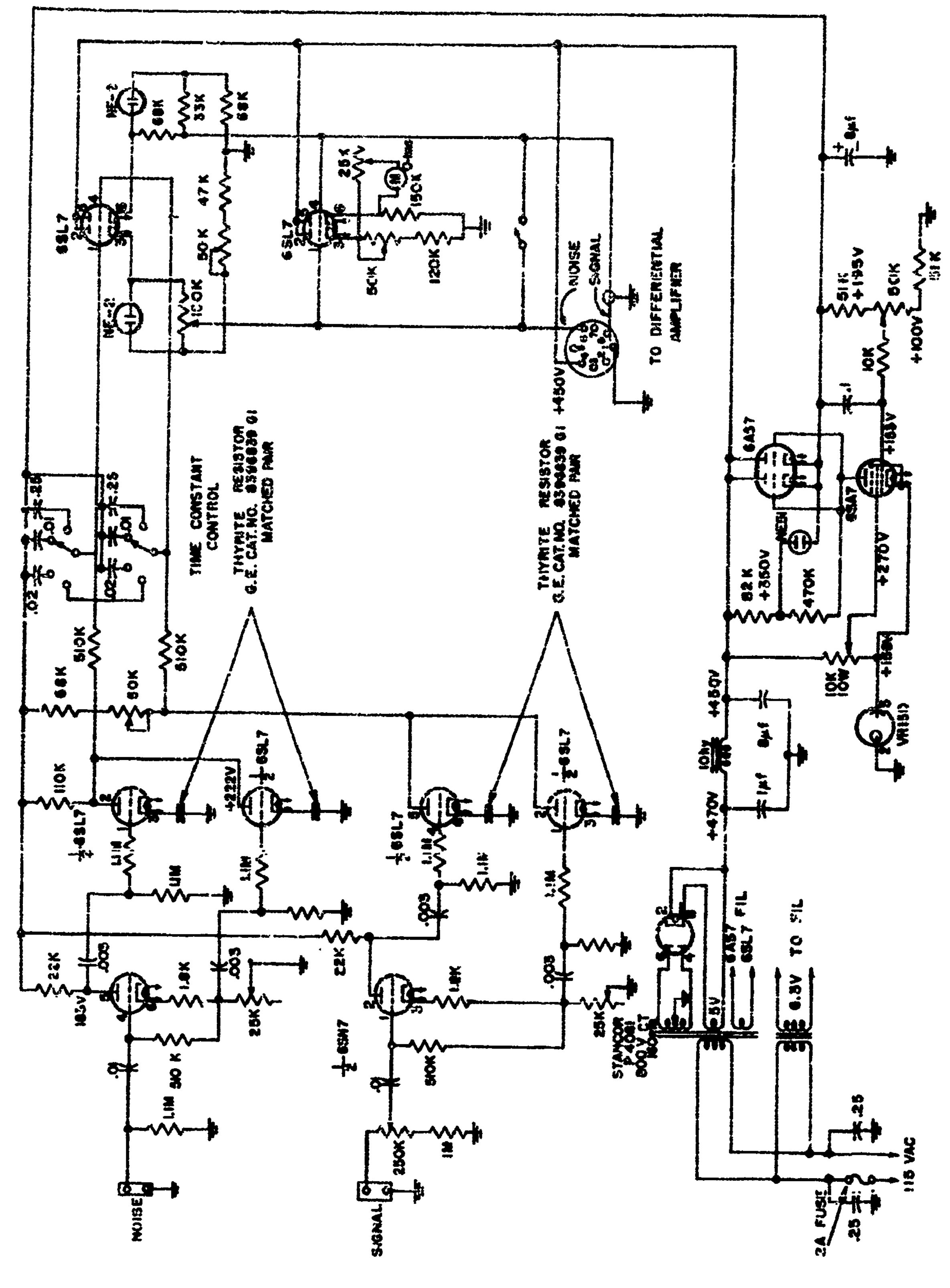

FIG. G-6
CIRCUIT DIAGRAM OF SQUARE LAW METER

CIRCUIT DIAGRAM OF SQUARE LAW METER

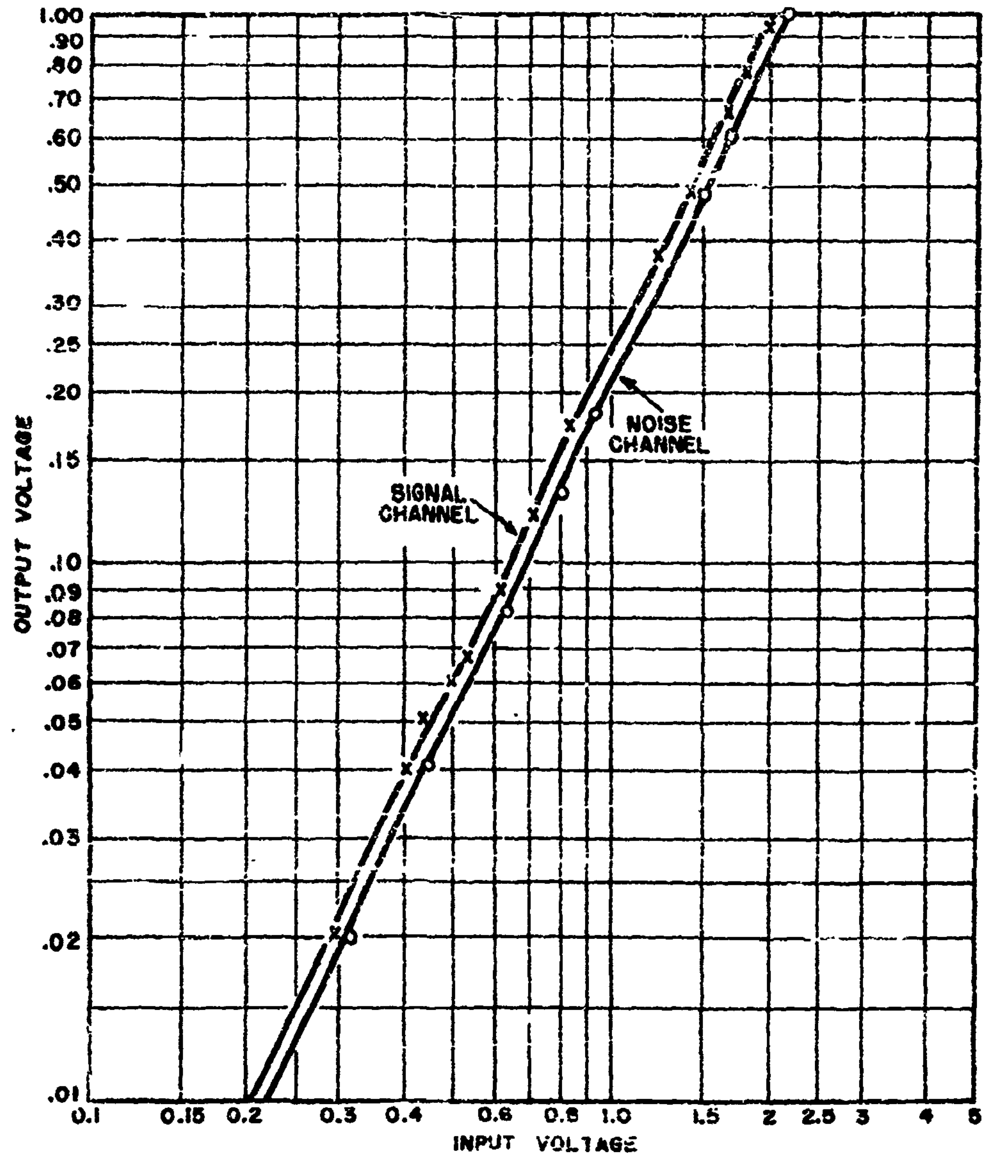

FIG. G-7

MEASURED VOLTAGE CHARACTERISTICS OF SQUARE-LAW METER

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APPENDIX H

DIRECT MEASUREMENT OF THE POWER TRANSFER EFFICIENCY OF LIAISON ANTENNA SYSTEMS*

A. INTRODUCTION

A comparatively simple means for the direct measurement of the power transfer efficiency of liaison antenna systems on aircraft has been devised. Equipment for carrying out this measurement was developed only far enough to show the feasibility of the method. It was utilized to determine the efficiencies, in the frequency range from 2 to 6 Mc, of the tail-cap and wing-cap antennas on the C-54 aircraft, and although the accuracy is not as good as desired, the results indicate that the method is practical. The accuracy could be improved by further development of the instrumentation.

The method consists of operating the antenna system over an image plane and measuring the effect of the energy reflected back into the system. The magnitude of the change in the reflection coefficient at the input to the system caused by this reflected energy can be expressed as a function of the power transfer efficiency of the system and known parameters. In applying this method to aircraft antennas, the aircraft is flown over a large body of salt water, which acts as a nearly perfect reflector in the 2 to 6 Mc frequency range.

B. METHOD OF MEASUREMENT**

In order to derive the expression which relates the power transfer efficiency to the reflection coefficient on the transmission line leading to the system, it is convenient to use scattering matrix notation.[1] In a

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* Prepared by D. R. Scheuch and John Taylor

** This method was devised by J. T. Bolljahn

[1] Montgomery, Dicke, and Purcell, *Radiation Laboratory Series*, Vol. 8, *Principles of Microwave Circuits*; pp 137 and 146, McGraw Hill Book Co.,Inc.

two terminal pair junction let a_1 represent the wave traveling toward the junction at terminals 1, and b_1 represent the wave traveling away from it, where a_1 and b_1 are normalized so that the power flow into the junction is given by

$$(P_1)_{in} = \frac{1}{2}(a_1 a_1^* - b_1 b_1^*), \qquad \text{(H-1)}$$

where the asterisk denotes a complex conjugate. Similarly, a_2 and b_2 are defined in a corresponding manner at terminals 2. Then

$$\begin{aligned} S_{11}a_1 + S_{12}a_2 &= b_1 \\ S_{12}a_1 + S_{22}a_2 &= b_2 \end{aligned} \qquad \text{(H-2)}$$

where the coefficients S_{nk} are constants of the junction. In the special case of an antenna over an image plane (Fig. H-1), $a_2 = a_1$, $b_2 = b_1$, and $S_{22} = S_{11}$. Under these conditions the system of Eq. (H-2) reduces the

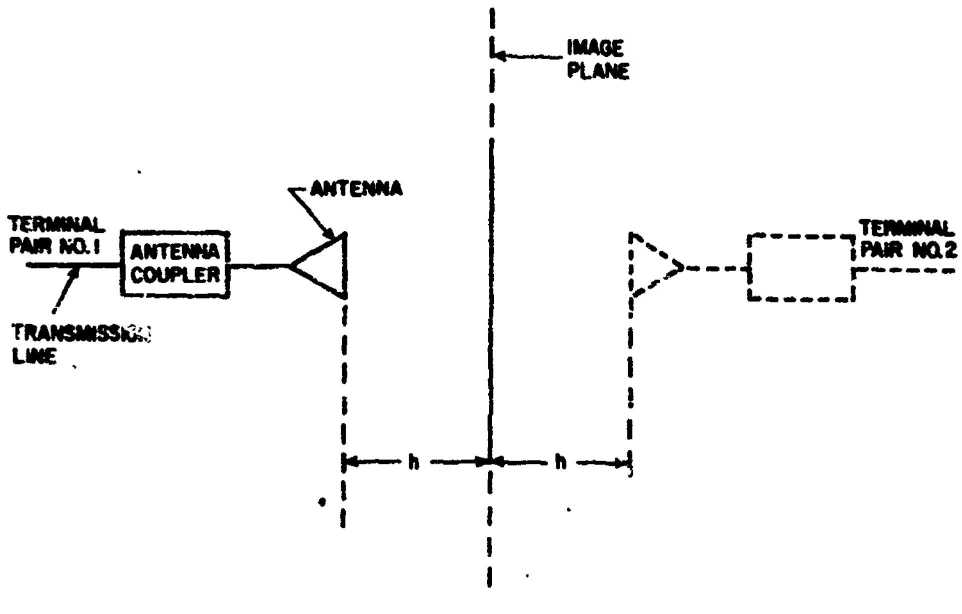

FIG. H-1
IMAGE PLANE METHOD OF MEASURING ANTENNA POWER TRANSFER EFFICIENCY

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single equation

$$a_1(S_{11} + S_{12}) = b_1 \tag{H-3}$$

The reflection coefficient, Γ, on the transmission line at terminal 1 is defined as

$$\Gamma = \frac{b_1}{a_1},$$

hence

$$\Gamma = S_{11} + S_{12} \tag{H-4}$$

If the image plane is moved to infinity S_{12} approaches zero, therefore when antenna 1 radiates into free space, the reflection coefficient,

$$\Gamma_0 = S_{11} \tag{H-5}$$

From Eqs.(H-4) and (H-5)

$$S_{12} = \Gamma - \Gamma_0 \tag{H-6}$$

When the antenna system at 2 is identical to the system at 1 but no power source is attached to terminals 2, and when the transmission lines at both terminals 1 and 2 are matched at the ends away from the antenna system, Eq. (H-2) becomes

$$\begin{aligned} S_{11} a_1 &= b_1 \\ S_{12} a_1 &= b_2 \end{aligned} \tag{H-7}$$

and

$$\frac{(P_2)_{\text{out}}}{(P_1)_{\text{in}}} = \frac{b_2 b_2^*}{a_1 a_1^* - b_1 b_1^*} = \frac{S_{12} S_{12}^*}{1 - S_{11} S_{11}^*}$$

In terms of the reflection coefficients

$$\frac{(P_2)_{\text{out}}}{(P_1)_{\text{in}}} = \frac{|\Gamma - \Gamma_0|^2}{1 - |\Gamma_0|^2} \tag{H-8}$$

Now the power transfer efficiency of the antenna system is defined by

$$\eta = \frac{P_t}{(P_1)_{in}} \tag{H-9}$$

where P_t is the power radiated by antenna 1.

Hence

$$P_t = \frac{1}{2} aa^* \left(1 - |\Gamma_e|^2\right)\eta \tag{H-10}$$

From Appendix F Section 3, the ratio of received power to maximum power available from the antenna is equal to the ratio of transmitted power to maximum power available from the transmitter for the same antenna system, when the input impedances of the receiver and transmitter are equal. Therefore

$$(P_2)_{out} = \frac{1}{2} b_1 b_1^* = P_t \frac{G_1}{4\pi r^2} A_2 \left(1 - |\Gamma|^2\right)\eta \tag{H-11}$$

where G_1 is the gain of antenna 1 in the direction of antenna 2, A_2 is the receiving cross section of antenna 2 in the direction of antenna 1 and r is the distance between the antennas. Since the two antennas are identical

$$A_2 = \frac{\lambda^2}{4\pi} G_1$$

Using this together with Eq. (H-9), Eq. (H-11) becomes

$$\frac{(P_2)_{out}}{(P_2)_{in}} = \left(\frac{G\lambda}{4\pi r}\right)^2 (1 - |\Gamma|^2)\eta \ . \tag{H-12}$$

From Eqs. (H-8) and (H-12)

$$\eta = \left(\frac{8\pi h}{\lambda G}\right) \frac{|\Gamma - \Gamma_e|}{1 - |\Gamma_e|^2} \tag{H-13}$$

where $h = r/2$ is the distance from antenna 1 to the image plane. Equation (H-13) is the relation which is used in the direct determination of the power transfer efficiency.

To obtain η, the aircraft is flown in gradual descent over a large body of salt water. The wavelength, λ, of the radiated signal is known and the distance, h, from the image plane is the altitude of the aircraft; the gain, G, is the gain of the antenna in the downward direction and can be obtained from model measurements. Both $|\Gamma_g|$ and $|\Gamma - \Gamma_g|$ must be obtained from data recorded during the flight. This is done in the following manner:

$$\Gamma = S_{11} + S_{12} \tag{H-14}$$

S_{11} depends on the adjustment of the matching network for the antenna and does not vary with the altitude of the aircraft. However, S_{12} is a function of the altitude. From Eqs. (H-7), for the case where the terminals 1 and 2 are matched,

$$S_{12} = \frac{b_2}{a_1},$$

and b_2 is proportional to the E field at the image antenna. Therefore,

$$S_{12} = A\frac{e^{-j2\pi\left(\frac{2h}{\lambda}\right)}}{2h} \tag{H-15}$$

where A is a constant. Thus when h changes by $\lambda/2$, S_{12} goes through a phase shift of 2π radians. The maximum value of $|\Gamma|$, and its minimum value are given, respectively, by

$$|\Gamma|\ \max = |S_{11}| + |S_{12}|,$$

$$|\Gamma|\ \min = |S_{11}| - |S_{12}|.$$

When $h \gg \lambda$ the change in $|S_{12}|$ while $|\Gamma|$ changes from a maximum to a minimum is negligible compared to $|S_{12}|$. Therefore

$$|\Gamma|\ \max - |\Gamma|\ \min = 2|S_{12}| \doteq 2|\Gamma - \Gamma_g|.$$

If the input to the antenna system forms one leg of the resistance bridge shown in Fig. H-2,* then the voltage

$$V_1 = V_0\left(\frac{Z}{Z + R_0} - \frac{1}{2}\right) = \frac{V_0\Gamma}{2}$$

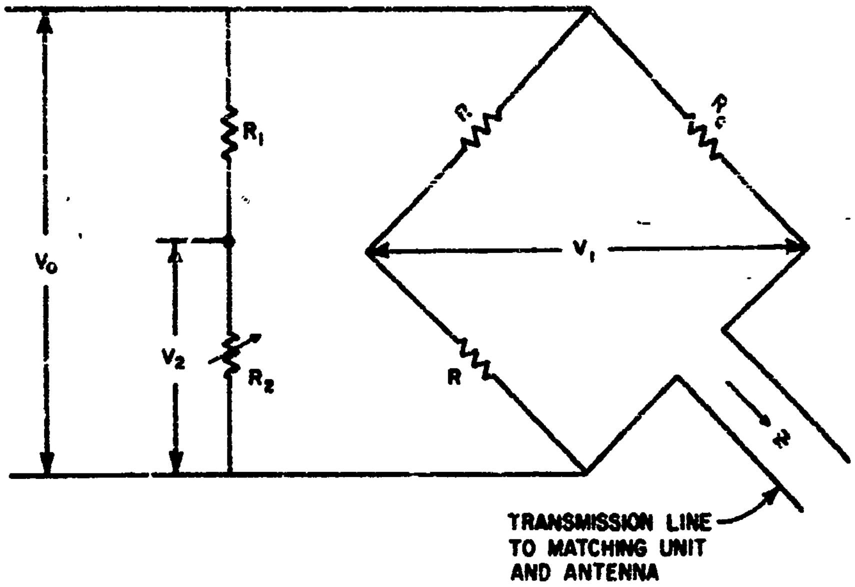

FIG. H-2
REFLECTION COEFFICIENT BRIDGE

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When $|V_0|$ is kept constant, $|V_1|$ oscillates as the altitude is decreased and the magnitude of the oscillations is proportional to $|S_{12}|$; by recording $|V_1|$ with an appropriate recorder the magnitude of these oscillations can easily be obtained. However, these oscillations may be small compared to $|\Gamma|$ and it is convenient to subtract a constant from $|\Gamma|$ before recording so that the oscillations will occupy the full scale of the recorder. To accomplish this for the measurements described here the average value of $|\Gamma|$ over several oscillations is obtained by using a circuit with a long time constant to detect the voltage V_1. The difference between $|\Gamma|$ as measured with a short time constant circuit and this

* This is the circuit used in a conventional standing-wave-ratio bridge.

average value of $|\Gamma|$ is then recorded. The same result can also be accomplished without the use of a long time constant circuit in the following manner. The voltage $|V_2|$ (Fig. H-2) is adjusted so that it is somewhat smaller than the minimum value which $|V_1|$ attains, and the two voltages, $|V_1|$ and $|V_2|$ are differenced before recording. Since

$$|V_1| - |V_2| = \frac{|V_0|}{2}(|\Gamma|-C)$$

where

$$C = 2\left(\frac{R_2}{R_1 + R_2}\right),$$

the small difference voltage is not greatly affected by small changes in $|V_0|$.

From the measured voltages $|V_0|$, $|V_1|$, and $|\Gamma|-C$, both $|\Gamma_0|$ and $|\Gamma - \Gamma_0|$ can be obtained, and η can be computed from Eq. (H-13).

C. RESULTS

The method of measurement described above was used to determine the power transfer efficiency of the tail-cap and wing-cap antennas on the C-54 aircraft. At the start of each measurement, the aircraft flew over the ocean at 3000 ft altitude; during the measurement a constant rate of descent of 500 ft per minute was maintained until an altitude of 1000 ft was reached. From the data recorded during the descent, the power transfer efficiency of the antenna system was computed.

Figure H-3 is a recording, taken during a test, of the voltage which is proportional to $(\Gamma - \Gamma_0)$. It can be seen from Eq. (H-14) that $|S_{12}|$ is inversely proportional to h, therefore the magnitude of the oscillations, D, recorded during the test should vary inversely as the altitude. As a check on the accuracy of the recorded data the magnitude of the oscillations was plotted against h (Fig. H-4). As can be seen, the product, hD, is a constant as required by Eq. (H-14).

The results of the measurements are shown in column 3 of Table H-I. These are compared with the antenna power transfer efficiencies estimated by the method described in Sec. 4.4.4.3 of Appendix A. While the agreement between measured and computed efficiencies is not close, it should

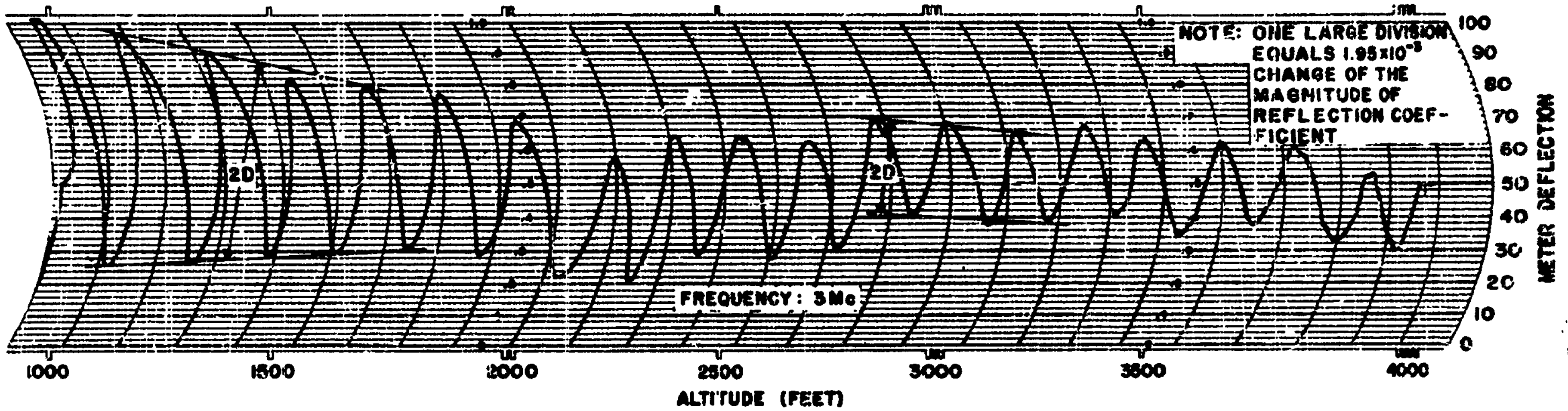

FIG. H-3

RECORDING OF CHANGE IN REFLECTION COEFFICIENT OBTAINED DURING FLIGHT TEST

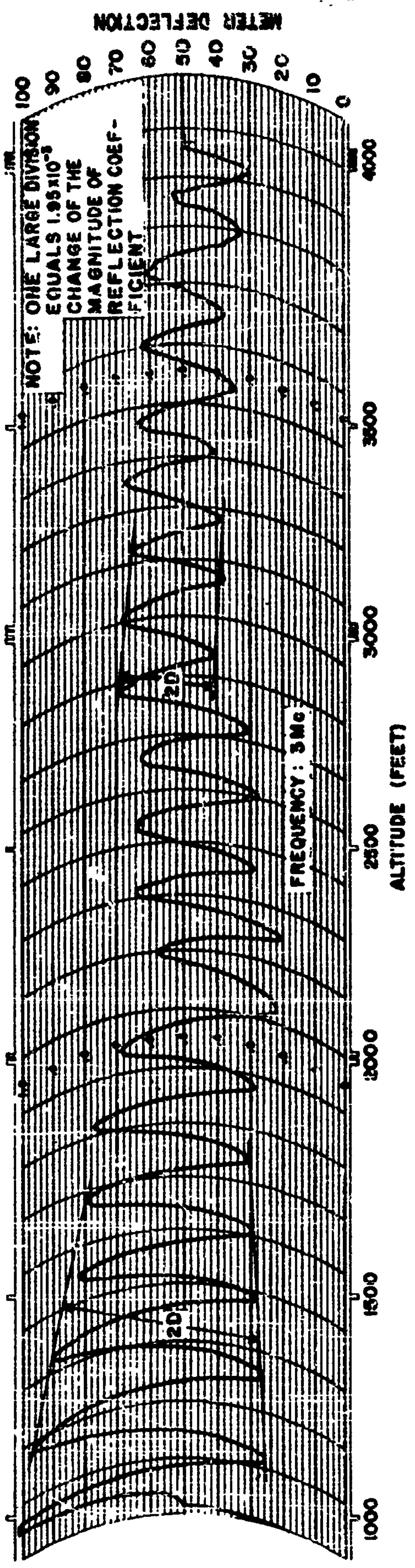

FIG. H-3
RECORDING OF CHANGE IN REFLECTION COEFFICIENT
OBTAINED DURING FLIGHT TEST

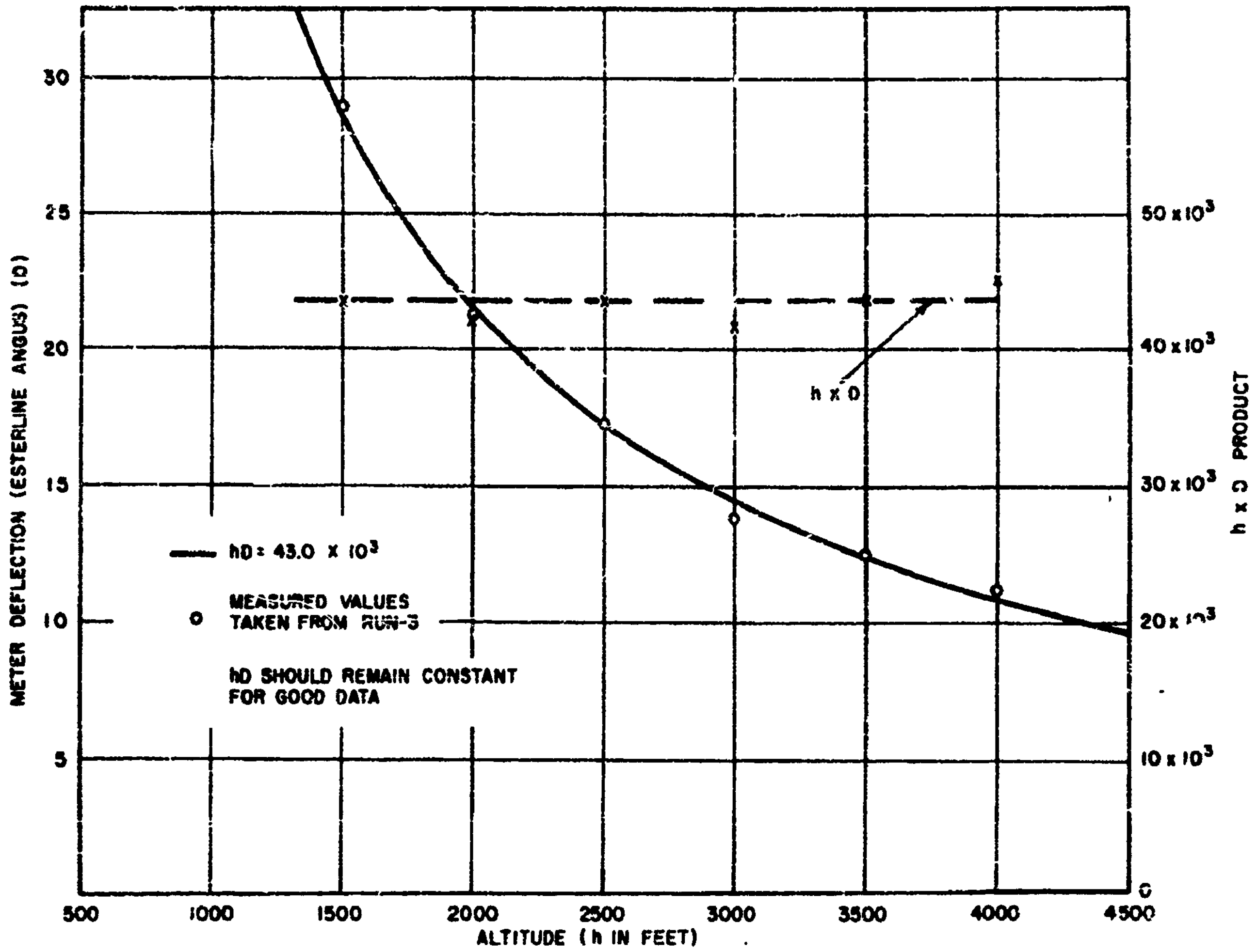

FIG. H-4
DIRECT MEASUREMENT OF EFFICIENCY - SAMPLE CURVE PROVIDING DATA CHECK

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be remembered that the results given in column 4 of the table are only an estimate. However, it is thought that the accuracy of the measured results could be considerably improved by further development of the measuring equipment.

TABLE H-I

DIRECT MEASUREMENT OF EFFICIENCY
SUMMARY OF RESULTS

ANTENNA	FREQUENCY (Mc)	ANTENNA POWER TRANSFER EFFICIENCY FROM DIRECT MEASUREMENTS	ANTENNA POWER TRANSFER EFFICIENCY ESTIMATED BY THE METHOD OF THE SPECIFICATION
Tail-Cap	2	9 %	3.5 %
Tail-Cap	3	45 %	33 %
Tail-Cap	4	97 %	68 %
Tail-Cap	6	19 %	40 %
Wing-Cap	4	96 %	75 %
Wing-Cap	6	76 %	70 %

APPENDIX I

A METHOD OF EVALUATING H-F AIRCRAFT ANTENNAS UTILIZING SCATTER-SOUNDING TECHNIQUES*

A. INTRODUCTION

The phenomenon of long distance backscattering of radiated h-f energy has been known for many years. Recently, backscattering techniques have been effectively utilized in the field of ionospheric investigation. The use of these techniques has been suggested as a convenient means for measuring the the comparative performance of several antennas under conditions of controlled range and relative direction of propagation.[1]

Long-distance oblique-incidence echoes are attributable to reflections from a remote ground area extending azimuthally an amount equal to the horizontal beam width and radially over a range of distance, beyond the skip zone, from which propagation may be supported under existing ionospheric conditions. The transmission time to the leading edge of the back-scatter echo is a reasonable measure of the skip distance. When signals from a rotating directive array are presented on a PPI display, the distant zones from which communications are possible are clearly indicated.

The same instrumentation and techniques can be applied to the comparative evaluation of either ground-based or aircraft antennas. The back-scatter transmitter and directive transmitting antenna array serve to illuminate a remote area on the surface of the earth, the location and size of which are determined by the choice of frequency, the prevailing ionospheric conditions, and the characteristics of the transmitting antenna such as beam width and orientation. This back-scattering of energy from the illuminated area over the return path provides simulation of signal transmission from this area. Furthermore, if one has control

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* Prepared by D. R. Schenck.

1 O. G. Villard, Jr. and A. M. Peterson, Scatter Sounding: "A Technique For Study of the Ionosphere at a Distance," Transactions of the IRE PGAP-3; Aug. 1952.

over both the transmitting frequency and the orientation of the transmitting beam, the location of the scattering signal source, within limits of ionospheric conditions, may be prescribed.

In Chapter 7 and in Appendix F, a detailed outline is given of the flight test evaluation of aircraft antennas. The evaluation of antennas in these tests is based on the difference in articulation score observed when using the different proposed antenna systems. These scores are obtained by calculation from the statistical distribution of the signal power received on the aircraft from a distant ground-based transmitter.

For the comparative evaluation using back-scatter techniques, flight procedures similar to these described in Appendix F are followed; however, the origin of the received test signal is the distant scattering sources rather than a remote ground station. The echo pulses are integrated to obtain the time average of the signal power received over each of the antenna systems. By flying the aircraft on a succession of different courses, a further averaging of received signal power is obtained over the azimuthal angle. The quantity measured for each antenna by this technique is proportional to the antenna system efficiency defined in Chapter 2, if it is assumed that the scatter sources are equivalent to distant ground-based transmitters. This assumption is justified, provided that the scatter transmitter is used with an antenna system having a sharply directive beam. The angular directions from which the signal is received at the aircraft from the scatter sources will, of course, be spread over a larger range, both in azimuth and elevation, than signals received directly from a remote station. An analysis similar to that carried out in Appendix D will show that this smearing out of the received signal directions will not affect the relative rating of the antenna systems, which is the basis of the evaluation method recommended in this report.

B. SYSTEM DESCRIPTION

The signals received by an airborne h-f communications receiver when flown within line of sight of a ground-based scatter-sounding transmitter will consist of a train of pulses having substantially the characteristics of the output pulses of the transmitter. Transmitted r-f pulses of 1-ms duration at a 25-cps repetition rate and a power level of 5 kw peak will reproduce high amplitude 1-ms pulses, separated in time by 40 ms, at the output of the receiver. If ionospheric conditions are such that back-scattering is occurring at the operating frequency, additional pulses

will be received. These are delayed from the direct pulse by an amount equal to the transmission time for the round trip path to the scattering area, and they are smeared in time by an amount which is proportional to the radial width of the scattering area. Since the average power density in the scattered field is independent of the orientation of the aircraft, the amplitude along this smeared echo envelope is a measure of the gain of the aircraft antennas.

If a sporadic E-layer of sufficient density is present at some point along the transmission path, additional back scatter pulses may be added to those propagated by the normal F-layer modes. These and other masking signals such as atmospheric noise make it necessary to perform a time selection of received pulses, monitoring the amplitudes of only those which occur within the interval of time which corresponds to the desired distance.

As previously described, the relative evaluation of the test antennas is performed by comparing the time average of received signal power for each antenna averaged over all azimuthal angles. To accomplish this, additional processing is required of the signal which has been selected by gating. Squaring is introduced during the detection process to make the system responsive to relative power. The time averaging of the received signal is performed by integration of the pulse train after detection. Additional instrumentation is required for antenna switching, for recording, and for timing the recording period on each of the antennas.

C. INSTRUMENTATION

It was necessary to design and construct only the airborne portion of this antenna evaluation system, since use was made of an existing ground facility. The Radio Propagation Laboratory at Stanford University cooperated by making their scatter-sounding transmitter and directive ground antenna arrays available for tests of the system. This equipment was capable of producing millisecond pulses at a repetition rate of twenty five cycles per second, with a power level of 5 kw, at a number of radio frequencies. Both rotatable Yagi antennas and switched vertical-V arrays were used in covering this range of frequencies.

A block diagram of the airborne equipment which was developed for antenna evaluation is shown in Fig. I-1. The three antennas under test, and their associated matching networks, are connected to a Collins 51-J

receiver through a time-sequenced coaxial switch. This permits each antenna to be sequentially connected to the input of the receiver for a preset interval of time. This switch also controls the timing clocks and magnetic counters in the integrating circuits which are associated with each of the antennas.

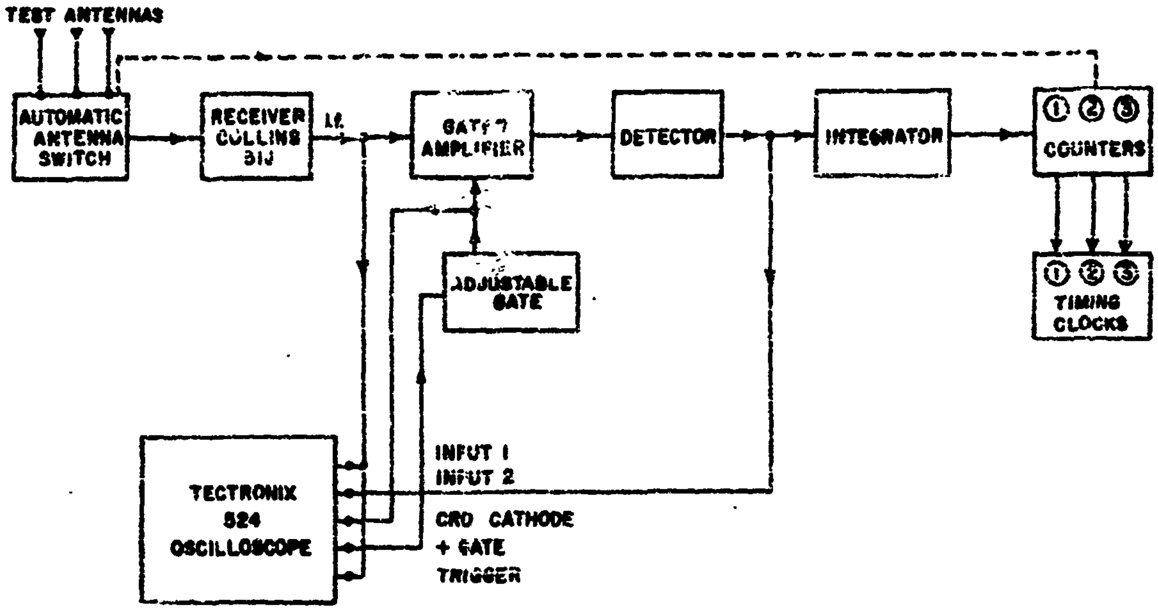

FIG. I-1

BLOCK DIAGRAM OF ANTENNA EVALUATION UTILIZING BACK SCATTER

The Collins receiver is operated in its broadest bandpass position without AVC or limiting. Under these conditions a linear range of operation of approximately 30 db is achieved. Signal from the receiver is taken from the 500-kc i-f low-impedance output jack. This signal is fed to both the external gated i-f amplifier and the Tektronix oscilloscope which is used for monitoring and synchronizing.

The Tektronix model 524 oscilloscope serves as the basic synchronizing element of the system, since the positive output gate from this instrument is used to control the adjustable gate circuitry associated with the gated i-f signal channel. Synchronization with the ground stations is obtained by adjusting the Tektronix so that the sweep is triggered by each transmitted pulse.

A diagram of the external circuitry is given in Fig. I-2. The adjustable gate generator which is triggered by the oscilloscope forms a gate that is variable both in delay from the transmitted pulse, and in width. Since this gate is used to turn on the signal channel, its width and position in time determines the width and range of the area from which echo signals will be accepted. The equivalent width adjustment is from approximately 100 to 900 miles, and the range is from 200 to 7000 miles.

The output of the adjustable gate circuit is also fed to the "CRO" terminal of the oscilloscope to intensity modulate the trace. This permits easy identification of the range of distances within which signals are permitted to pass through the gated i-f amplifier.

The two double triodes, V-1 and V-2, form the complete gated i-f amplifier. Signals from the Collins receiver are passed through this amplifier only during the interval of time corresponding to the width of the gating signal.

Video detection is accomplished in V-3. D-C restoration is applied to the i-f pulse before detection, in order to utilize the entire linear range of tube V-2. Time constants are such that sharp variations in the pulse envelope may be readily followed. The maximum gain from the receiver output to the detector output is approximately 300. The maximum peak value from the detector output is -90v.

A squaring circuit whose dynamic range is comparable with the rest of the system (approximately 30 db) should follow the detector to permit the evaluation to be based on integration of the average power of the received signals. Although the design of such a circuit should present little difficulty, time did not permit its incorporation.

The output of the detector circuit is fed into a simple RC integrator to give rise to an essentially d-c voltage. This d-c voltage is then converted into a sawtooth voltage of constant amplitude. As long as the charging voltage is several times the sawtooth amplitude, the sawtooth frequency will be a linear function of the charging voltage. The range of this device is greater than the required 30 db, as can be seen in Fig. I-3. Figure I-4 shows the transformation of the d-c voltage into a sawtooth waveform.

Register of the integration is performed by a cumulative counting of the sawtooth frequency, using magnetic counters. The counter is actuated

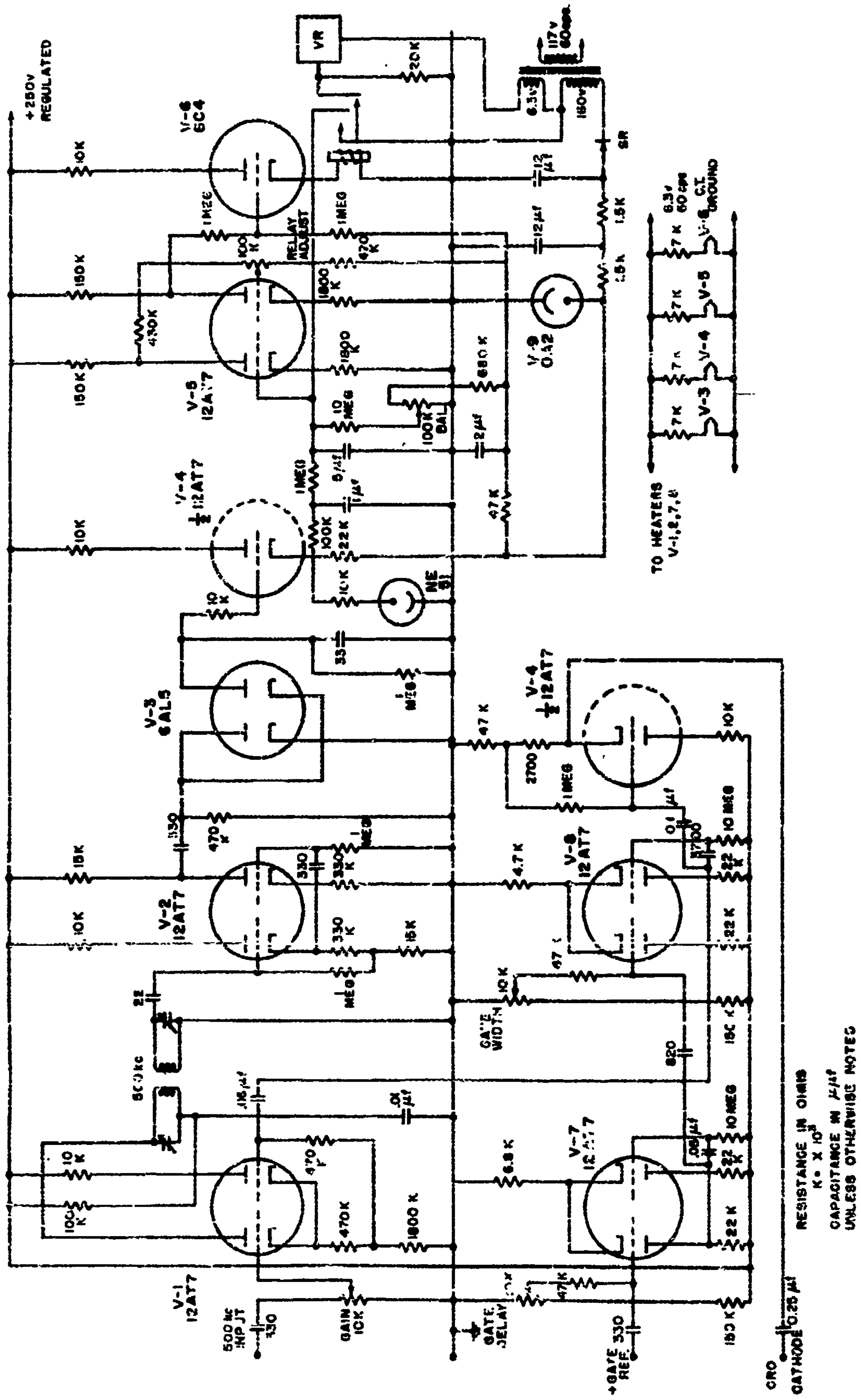

FIG. I-2

GATED AMPLIFIER, GATE, DETECTOR, AND INTEGRATOR FOR ANTENNA EVALUATION UTILIZING BACK SCATTER

C-806C-F-296

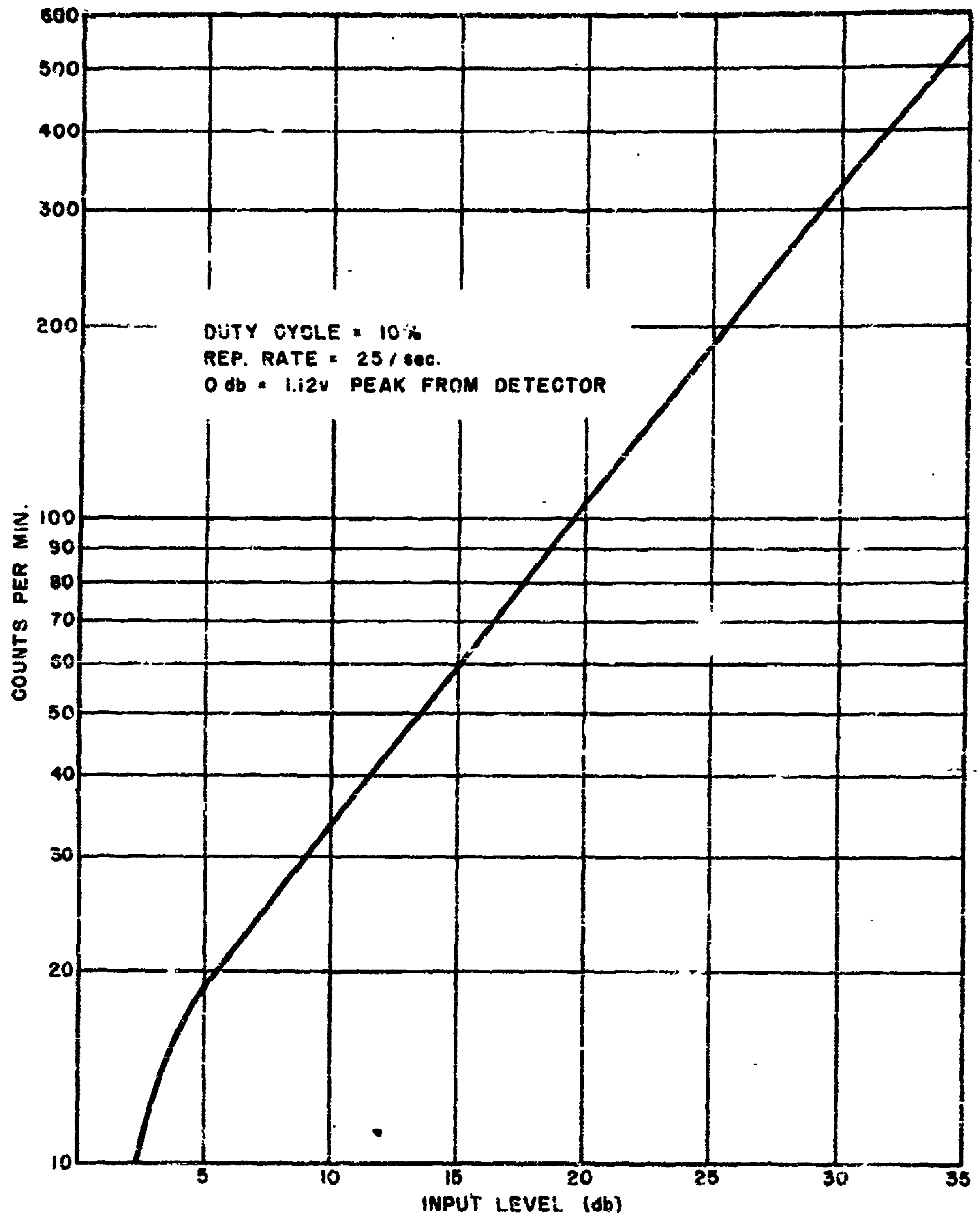

FIG. I-3

OUTPUT COUNT AS A FUNCTION OF INPUT PULSE LEVEL

B-606C-F-256

by the re-cycling relay which forms a part of the integrating circuit. Tubes V-5 and V-6 provided sufficient d-c amplification beyond the RC integrator to satisfactorily operate the re-cycling relay. This arrangement gives satisfactory counting operation from approximately 20 to 900 counts per minute.

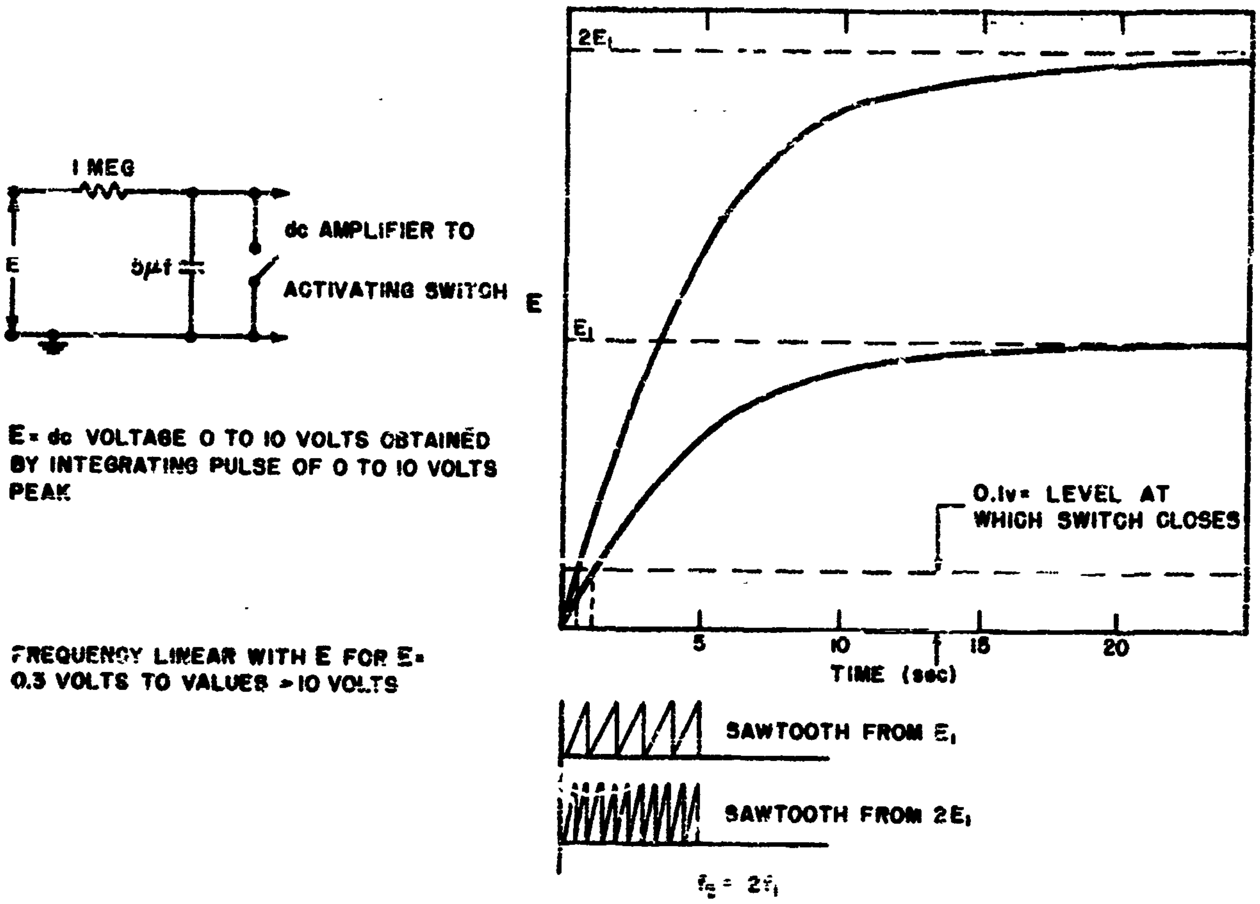

FIG. I-4

CONVERSION OF THE INTEGRATED DC TO A SAWTOOTH TO PROVIDE A LINER COUNT

B-606C-F-297

Three counters and three timing clocks are used; a separate counter and clock is associated with each of the three antennas under test. Switching information derived from the antenna switch is used to select the appropriate clock and counter for the antenna in use. The clocks measure the total time that each antenna is in use during a particular test, while the magnetic counter registers the integrated signal corresponding to this period of time. Inequalities in timing can thus be corrected for at the conclusion of each test run.

D. EVALUATION OF THE EQUIPMENT

Time did not permit an extensive evaluation of the equipment. Development was carried only to a point which would permit an appraisal of the feasibility of the scheme. A single flight test was performed on 5 May 1953, on board the C-54D aircraft. The object of the flight was to compare the three antennas on the aircraft while flying the normal hexagonal test patterns. The tests were conducted at 12.8625 Mc on a signal originating at Stanford University. The equipment proved flightworthy with no evidence of malfunctioning. At distances of about 100 miles from the transmitter, no difficulty was experienced in obtaining synchronization. Complete test data on the antennas was not taken, due to a failure of the main power supply system on the aircraft. Additional in-flight checks were not possible because of unavailability of the aircraft. Several tests were performed on ground antennas, with promising results.